University of Alberta

A Fuzzy Logic Model for Predicting Commercial Building Design Cost Overruns

By

Karla Grace Knight ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment
of the requirements for the degree of Master of Science

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ABSTRACT

This research develops a model for predicting design cost overruns and underruns on commercial building projects. The model uses fuzzy logic to relate characteristics of the project with potential risk events to predict a percentage cost overrun or underrun above or below the estimated fee. The research identifies and discusses the most significant project characteristics and risk events on design projects, discusses issues related to scope creep and the importance of project scope definition, develops the framework for a model using fuzzy binary relations, and implements and tests the model in a computerized environment.

A local consulting engineering firm participated in the research by identifying the need for this research, offering their expertise and knowledge to help determine the factors for the model, and providing data for development and testing of the model. The data was solicited through interviews with project managers within the company, gleaning information from their knowledge base of project management, and from their experiences on specific design projects. Through testing and calibration of the model, the model was proven successful in accurately predicting design cost overruns and underruns, both in numeric form and using linguistic descriptors.

The model proposed in this research is for use during the design phase on commercial building projects. It provides project managers with a tool to aid in the decision-making process when estimating and negotiating fees. The use of fuzzy logic in the model enables both the user input and the output to be described in subjective terms, which suit the nature of the decision-making process used in establishing design fees.

The model therefore demonstrates the usefulness of fuzzy logic in modeling decision-making processes used in the construction industry.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

SS_1	Strength between a project characteristic and risk event
P_i	A project characteristic
R_k	A risk event
C_m	A percentage cost range
SS_2	Strength between a risk event and cost range
wP_i	Rating of a project characteristic
wR_k	Rating of a risk event

Abbreviations

APEGGA	Association for Professional Engineers, Geologists and Geophysicists of Alberta
AAA	Alberta Association of Architects
CII	Construction Industry Institute
PDRI	Project Definition Rating Index
Max-min	Maximum-minimum
Max-product	Maximum-Product
Cum-min	Cumulative-minimum
COA	Center of area
MOM	Middle of maxima
LOM	Largest of maxima
SOM	Smallest of maxima
RFI	Request for information
PC	Prime consultant
VB	Visual Basic
Abs	Absolute

1. INTRODUCTION

1.1 Introduction

Research in the construction sector is mainly focused on management of the construction phase of a project rather than on the design phase. Eldin (1991) believes one reason for this is that the cost of the construction phase is much higher than that of the design phase. There are many more tools in place to help manage construction such as estimating programs, monitoring and tracking programs, scheduling programs, tools to aid in the management of resources such as personnel, equipment and materials, and many more. Design management, on the other hand, is much less structured, less organized and the process less monitored. This allows for a greater potential for an unsuccessful project.

A project may be deemed unsuccessful for many different reasons. For example, success can be measured from customer satisfaction, user satisfaction, ease of construction, design effectiveness, design quality, efficiency, productivity, timeliness, and profitability. For most design firms though, the bottom line will be the cost of design and whether the appropriate fee for the work was paid. The catalyst that began this research was the issue of scope creep, which is quite often the cause of cost overruns.

Although the design phase represents a small portion of the overall cost of a construction project, McGeorge (1989) believes that "constructability and value engineering yield construction cost savings of ten to twenty times the cost of the extra design input." The catch is that since the cost of design is so much less then the cost of construction, it actually requires a significant increase in design effort for a small reduction in construction cost. For example, McGeorge claims an increase in design input of 50% will lead to a 10% savings in construction costs. But a better design and better management of the design process will lead to a more organized and controlled project and therefore a more successful project. Design deviations account for approximately 60% of construction project deviations, and poor quality design and engineering can cost a project almost 10% of the total cost of the project according to Bubshait et al. (1999). On a construction project everyone must work as a team. We are all aware of the old adage "a chain is only as strong as its weakest link"; this can also apply to a construction project. Therefore it only makes sense that proper design management and control should be an important issue, and not only to the engineering design firms but to the construction industry as a whole.

The problems associated with design costs and risks in the design phase are often problems that will continue throughout the entire project, thereby affecting the construction phase and the cost of the entire project. Being aware of these problems at the onset of the project and taking steps to minimize the risks they present will benefit the entire project and all parties involved. Due to limited project tracking during design, it may not always be obvious when a project runs off track of the estimate and why the project is over budget. The model presented in this thesis will help to identify why potential problems on the project may arise, what the problems will be, and the potential outcome on the project cost. If a project manager is aware of these problems at the onset of the project, the project manager may then take more care in controlling the project and potentially preventing higher project costs than anticipated. For this research, the design phase is relative to the work of the engineering design consultant, who is hired after the project conception and after the project requirements have been determined.

1.2 Controlling and Defining Scope

A lack of scope definition at the onset of a project is one of the main causes of cost overruns during design. A cost overrun occurs when the actual cost of the design to the design firm is above the fee paid to the design firm to complete the work, assuming a project fee estimated at the onset of the project. The Construction Industry Institute's publication on Scope definition and control (1986) ranks the loss of scope during engineering as having the second highest impact on cost overruns. Dysert (1997) claims that "poor scope definition at the estimate stage and loss of control of project scope" are the most frequent contributors to cost overruns. A poorly defined project is subject to changes initiated by the client that will require extra work and effort by the design team to complete. Minor changes to the scope throughout the design phase can add up and lead to major cost overruns on the project. This is known as creeping scope. Scope creep is the addition, as development proceeds, of new features to a project that are above and beyond what the original contract called for. With a poorly defined scope there is no baseline against which changes can be evaluated and monitored to identify those that are not within the original scope of work. According to Dumont et al. (1997) these changes may result in cost overruns and a greater potential for disputes. Dumont also claims these changes may "delay the project schedule, cause rework, disrupt project rhythm, and lower the productivity and morale of the workforce." But an increased level of scope definition will "improve the accuracy of cost and schedule estimates as well as the probability of meeting or exceeding project objectives." A survey done by Bresnen et al. (1991) showed that of projects surveyed that were over budget, 40% of the time it was due to additional work and/or design variations.

Scope creep is a problem that is often easily identified by project managers on their projects, but they may have reasons for not pointing out to the owner or architect that extra work is being done. Often the amount of extra work is minimal and the project manager may want to avoid confrontation with the owner and so will not ask for extra money as it could affect future relations with the owner. Another factor that affects whether a consultant receives extra money for extra work done is the prime consultant. The prime consultant may be unwilling to approach the owner for extra fees or perhaps it is a contract issue not allowing them to. Some contracts between the prime consultant and the owner will stipulate that all extra work will be done at a specific rate, which may be much less than what the consultant would normally charge, again causing the consultant to lose money. All these minor amounts of extra work can add up and create a large difference to the bottom line.

A poorly defined scope can also be caused by internal problems within a design firm. If the project manager does not adequately define the project and tasks to be done to the designers and drafters, extra work may be done due to lack of direction. A project manager must have good communication with the design team and provide guidance and direction to ensure everyone is working towards the same goal. Misunderstandings and misinterpretations between parties working on the project can cause problems such as rework and extra work and will invariably cause disputes between the parties. Good communication, good organization and control, and proper scope definition are therefore important elements of a successful project.

1.3 Background to the Topic

Sun (2000) developed a model for use in evaluating and predicting design performance. Her work identified factors that affect design performance and created a fuzzy expert model to predict the impact of these factors on design performance. She developed a list of fourteen input factors, each with multiple sub-factors, and three output factors to measure design performance. The input factors deal with company characteristics, market conditions, project characteristics for design and construction phases, and characteristics of the owner and vendors. The output factors were cost, schedule and accuracy of design documents. Data was collected using a mail-out survey questionnaire asking questions that elicited numeric and linguistic responses from experts in the field of industrial construction engineering. The survey was mailed out to numerous industrial contractors in Alberta and British Columbia.

Originally, this thesis project set out to further develop Sun's model by changing certain characteristics of the model, changing the data collection techniques, and refining the model. The major change of the model was to change the focus from industrial construction to commercial building construction. The intent for data collection was not to use a mail-out survey but instead to work with one specific company and have access to their projects and personnel to collect the data necessary for the model.

A local design firm was targeted to approach and ask for cooperation with the data collection portion of the research. This company was chosen based on their reputation in the community, their involvement with the University of Alberta, the type of work they were typically involved in, the size of the company, and their willingness to contribute to construction research. The company reviewed the proposed research topic.

Although they liked the idea, they suggested that a more pressing topic to research, and one that they had in fact set up a task force to address, is the issue of scope creep.

They found scope creep particularly to be an issue because when preparing an estimate, most engineers did not have much time to prepare it and therefore were not able to take the time to properly define the scope. The company needed a tool to help this process and make it quick and easy for the project manager or engineer to define the scope of work. A checklist of scope items was proposed as an output of the future research.

The first attempt at modeling the problem of scope creep was to use the fee proposal letter and to compare the work breakdown used to prepare the estimate with the actual work that was done, and to compare the estimated and actual cost breakdowns. The plan was to identify deviations in the scope, determine how to quantify these changes, identify the factors causing the changes, and determine the impact on the cost or schedule. The data was to be gathered from the project files. After reviewing project files it was quickly realized that the data necessary was not available.

The method of attacking the problem of scope creep was subsequently revised to determining the characteristics of a project that make it more prone to scope creep, looking at the risk factors during design and construction that lead to scope creep, and assessing scope creep based on its impact on the project cost. Data was to be accumulated not from the project files but from interviews with the project managers. This, however, would be impossible to do because cost impacts from scope creep could not be singled out of the total project cost and so the scope was broadened, arriving at the current topic, to cover all factors (including scope creep) and risks that lead to cost overruns on a project.

1.4 Thesis Objectives

The objectives of this thesis are as follows:

1. To develop a checklist of items requiring proper definition prior to design in order to achieve proper scope definition.
2. To identify the characteristics of a design project that contribute to cost overruns. The characteristics that have the greatest potential to affect project performance and the most frequently occurring adverse project characteristics will be identified.
3. To identify the risk and opportunity events that contribute to cost overruns and underruns. The most common risk/opportunity events found in projects and those having the greatest impact on project costs will be identified.
4. To create a model that will accurately predict cost overruns and underruns, as a percentage of the contract fee, based on the degree of existence of certain project characteristics and the degree of occurrence of certain risk/opportunity events.
5. To show the usefulness and applicability of modeling construction problems using fuzzy set theory.

1.5 Research Methodology

As described in a previous section, the topic for this thesis was arrived at through consultation with a design firm, which was instrumental in identifying the need for and relevance of this research. After determining the problem to be addressed and the input and output of the model, a literature search was done to identify project characteristics and risk events that affect construction design projects. Engineers from the cooperating company then helped to refine the factors in the model by identifying those that had the greatest impacts on their projects and were recurring events.

Data were collected by interviewing project managers and other personnel within the company. First, a panel of experts was assembled to determine the standard strengths to be hard coded into the model. Then further individual interviews were done with the project managers to collect data on previous projects that were used to test the model. Two questionnaires were developed in order to conduct these interviews. This process will be discussed further in Chapter 4.

The model was programmed into Visual Basic 6.0 in order to ease the process of inputting data and calculating the output. Using the data obtained from the project manager interviews, the accuracy of the model was tested by comparing the predicted outputs to the actual cost overruns or underruns. The model required some calibration to produce more accurate results, and was then retested to the satisfaction of the evaluation criteria developed.

1.6 Thesis Outline

The introduction to this thesis discussed the relevancy of the chosen topic and some background data to define the issue of scope creep and reveal the process that identified the need for this research.

Chapter 2 is a literature review on other research that identifies problems that contribute to design cost overruns and models the effects on design projects. Fuzzy logic and fuzzy set theory were also researched. This chapter identifies models of construction applications that use these techniques. Binary relations, the technique used in this research, are introduced and discussed and multiple composition operations and methods of defuzzification are reviewed.

Chapter 3 identifies and discusses the project characteristics and risk events that were chosen for use in this model. It explains the framework of the model, how the factors are related to each other and the output, and describes the calculations used by the model. The applications and uses of the model are also explained.

Chapter 4 reviews the data collection process. Data for testing the model and calculating the output was solicited from project managers using interview questionnaires. The development of the questionnaires, the interview methodology, and an analysis of the data received are discussed in this chapter.

Chapter 5 provides the testing, calibration, and validation of the model. The performance of the original model was unsatisfactory, but calibrations to the model improved its accuracy with respect to the data collected on completed projects.

Chapter 6 reiterates the thesis objectives and concludes this thesis. The limitations of the model are discussed and suggestions made for future development of the model.

2. Literature Review

2.1 Introduction

Literature on design cost control and cost overruns is very limited. Many of the factors that affect design costs have been identified and studied, but no tools are currently in place for predicting design cost overruns. Project management of the design phase is under-researched in comparison to the amount of research that has been done on project tracking, monitoring and control for the construction phase of a project. Factors for the model proposed in this thesis were chosen partly by a literature search that reviewed those issues that are important to design work, and partly through discussion with project engineers and other personnel working with a design firm. The first part of this literature review will cover studies that have been done on factors that affect design costs. The next sections are on fuzzy logic, modeling with fuzzy logic, and the techniques that are used to create the proposed model.

As mentioned, studies have been done on the factors that influence design costs such as work done by Cox et al. (1999). The authors claim that changes in design that are made after the construction contract is awarded will incur costs of 5 to 8%. The most common reasons for changes in design are:

- Designer's omissions in tender documents,
- Coordination defects in tender documents,
- Change forced upon the project from shop drawing coordination,
- The employer has changed his requirements, and
- New information on existing ground conditions.

Glavinch (1995) reports on the issue of constructability and its effect on the construction process. Here the author suggests that the architects and engineers are responsible for the constructability of their designs and should realize that poor constructability will slow down or impede construction and lead to delays, insufficient use of resources, and out-of-sequence work. This not only affects the construction contractor, but the design firm as well. The designer is responsible for possibly re-designing, solving problems regarding the design, answering questions when the contract documents are not clear, and attending meetings and making site visits to rectify the situation. These tasks all cost the consultant extra money that was not originally anticipated.

2.2 Models of Factors Affecting Design Costs

A model designed by Love et al. (2000) uses the factors that contribute to design errors to simulate practical scenarios in order to reduce design errors, which will subsequently reduce rework in construction. Love reports that the direct costs of rework in construction projects are 10-15% of the contract value and the main causes of rework are design changes, errors and omissions. The model is to be used to assist architects and engineers with particular situations they may be faced with when managing a project. The issues the model deals with are:

1. Productivity and accuracy of selected project staff from company resources or new employees;
2. Assigning design tasks to project staff;
3. Error proneness during design; and

4. Re-designing due to errors found by the construction contractor in the contract documents.

The output of the model includes the number of tasks designed erroneously, the time necessary for design completion, extra time necessary for construction completion due to errors in design, the number of activities needing redesigning, and the effort spent on re-design in person-weeks. Output can be given for different scenarios involving differing experience of design personnel, shortened or lengthened design time, and uses of out-of-company resources. The model presented here uses the simulation package Powersim CONSTRUCTOR 2.5 to write the computer code and convert influence diagrams into flow diagrams that model the processes.

The authors claim industry practitioners have tested and validated the models ability to predict the behaviour expected of the input situation. This model is simply a tool to assist a project manager with his or her management strategies and decision-making and demonstrates the significance of the impact of design errors on the construction process. Although this model seems quite effective in modeling the causes and effects of design errors, design errors are only one of the many factors that contribute to design cost overruns.

Scope creep and scope definition, which are discussed in the previous chapter, are important factors that affect design cost overruns. The Construction Industry Institute (CII) has performed significant studies into the issue of scope definition. The CII prepared a publication entitled 'Scope Definition and Control' (1986) that discusses the effects of a poorly defined scope on the estimate and quantity take-offs, and changes to the project scope. A further study by the CII produced the 'Project Definition Rating

Index' (PDRI) for industrial projects (Dumont et al., 1997), and a PDRI for commercial building projects (CII, 1999).

The PDRI is a "powerful and simple tool" that offers a "method to measure project scope definition for completeness" (CII, 1999). It is essentially a checklist of scope definition elements broken down into three sections: basis for project decision, basis of design, and execution approach. These sections are further broken down into the following categories:

- Business strategy
- Project requirements
- Building programming
- Equipment
- Deliverables
- Project execution plan
- Owner philosophies
- Site information
- Building/project design parameters
- Procurement strategy
- Project control

A score sheet accompanies the checklist which the user can use to rate the definition of each of the scope elements on a scale from 0 to 5. Each rating of each element has an associated weight; these weights are summed up to produce the total score. A score of less than 200 signifies excellent project scope definition whereas a project with a score greater than 200 may have cost and schedule issues as well as a number of change orders. The difference between a positive score (<200) and a negative score (>200) is cited as a 1% cost underrun versus a 6% cost overrun.

The PDRI is applicable to a number of different building projects such as offices, banks, shopping centers, airports, athletic facilities, and many more. It can be used by owners, designers and constructors to evaluate the project and to help identify poorly defined project scope definition elements.

The PDRI is a very useful tool for evaluating a project and helping to define the project scope. Again, the issue of scope definition is just one of the many factors that can cause cost overruns for a design firm. The checklist provided is quite broad as it covers the owner's, designer's and contractor's responsibilities, so any company wishing to use it may need to tailor it to suit their project tasks.

Kometa et al. (1996, 1995) have researched the risks inherent to consultants due to the client on a project. The research has found that "a plethora of client attributes affect project implementation." Consultants have typically focused only on a client's financial status as a means of evaluating and assessing the client. The model proposed by Kometa takes into account other attributes of the client and evaluates their possible effects on "project performance and financial well being of the consultants." The model was validated by using historical project data from 29 construction projects and questioning the respective consulting firms on the client's attributes at the onset of the project.

The list of attributes used in the model is quite extensive and covers the areas of:

- Project feasibility
- Financial stability
- Project characteristics
- Past experience
- Current market conditions
- Client duties
- Past performance
- Organizational quality
- Quality of management
- Client characteristics

Each main attribute has anywhere from 1 to 10 sub-attributes. The attributes are all given a weight constant that signifies the influence that attribute has on the project performance, and a merit value signifying the extent that the attribute will affect the performance and commercial viability of the consultant. These two values are multiplied to get the risk exposure index.

The model uses the project outcomes of time, cost, fees and quality in order to determine the success of the project. The data for time, cost and fees are obviously based on the actual numbers for the project; quality assessment is based on ratings, given by the consultant, of functionality, technicality, aesthetics, comfort, and prestige. A weighting is calculated for each outcome and combined to get the Aggregate Project Outcome (APO), expressed as a percentage. The final output of the model is the overall risk exposure, *I*, expressed as a percentage, that a consultant faces in accepting work from the client.

The model is intended to be used by consultants, or possibly contractors, to evaluate a client and their project, but can also be used by the client as a self-assessment tool. The model cannot be used until the consultant has adequate information on the client and the project, but early implementation of the model will help the consultant to determine their risk exposure if the work is accepted. This model appears quite comprehensive, but again, the client is only one of the risks inherent to a consultant on construction projects. The model should evaluate the entire project team, i.e. the architect, prime consultant, and other consultants and specialists, in order to accurately evaluate the risk to the consultant.

The work of this thesis advances the topic of design cost management by developing a model that predicts design cost overruns by accounting for a multitude of factors that cause cost overruns.

2.3 Uses of Fuzzy Logic in Construction

Construction applications are increasingly using computer modeling techniques to help make decisions and estimate costs, performance, quality or time. Fuzzy set theory and fuzzy expert systems are used increasingly in situations where little deterministic data are available. Fuzzy logic and fuzzy set theory were invented by Zadeh in 1965, and has since been continuously used and taught in many sectors of industry. "Fuzzy set theory was originally devised to model uncertainty associated with human perception or subjective probability judgments" (Nguyen, 1985).

Due to the imprecise nature of many factors that affect construction projects, and a general lack of data for proper quantification of factors, fuzzy logic lends itself nicely to many construction applications. The measurement of construction factors is often subjective and uncertain where actual data are not available or when the data comes from the experience and judgment of those in the industry. For this reason, fuzzy logic is being used more and more to model construction issues where the process was previously only available in the mind of an experienced construction employee. Fuzzy logic supports the use of linguistic variables such as "high experience" or "bad weather" and allows for ranking or subjective rating of factors used in models.

Fuzzy set theory has been used for construction management applications such as risk assessment (Kangari and Riggs, 1989; Tah et al., 1993; Guyonnet et al., 1999) and pricing construction risks (Paek et al., 1993). It can also be used for project control issues such as scheduling (Ayyub and Haldar, 1984), estimating precipitation impacts for scheduling (Smith and Hancher, 1989), project network analysis (Lorterapong and Moselhi, 1996), cash flow analysis (Boussabaine and Elhag, 1999), evaluating alternative construction technology (Chao and Skibniewski, 1998), crane selection (Hanna and Lotfallah, 1999), and assisting in selecting corrective actions when problems arise on the construction site (Russell and Fayek, 1994). The bidding and tendering phase of a project can also benefit from fuzzy set theory with models that aid in contractor pre-qualification (Elton et al., 1994), tender evaluation (Nguyen, 1985), and setting a margin or mark-up for bidding on construction projects (Fayek, 1998).

There are many software systems available that support fuzzy expert systems, such as Matlab, and System Z-II described by Leung and Lam (1988). Fuzzy expert systems utilize If-then rules for reasoning and membership functions to handle linguistic variables. They have been used for construction applications such as cost estimating (Mason and Kahn, 1997), risk management (Kangari and Boyer, 1987), resource allocation (Chang et al., 1990), and industrial applications such as controlling the operation of cement kilns (Holmblad and Ostergaard, 1982).

The concepts and definitions in fuzzy logic are explained well in books by Klir and Yuan (1995), Klir, St. Clair and Yuan (1998), Pedrycz and Gomide (1998), Yager and Zadeh (1992) as well as other books and articles by these authors.

The model presented in this thesis uses fuzzy binary relations and fuzzy set operations to calculate the output of the data. Certain operations on fuzzy binary relations, namely the composition operation and methods of defuzzification, will be reviewed and discussed.

2.4 Modeling with Fuzzy Binary Relations

Binary relations are a fuzzy set theory technique that involves approximating the relationship between two data sets given the degree of association between the sets. The advantage of using binary relations is they do not rely on membership functions, which can require substantial data sets formed on expert opinions; this is unfortunately also the biggest weakness of binary relations because the user must provide ratings instead, which are often subjective and relative to the user's context. Binary relations are most simply expressed in the form of matrices, but can also be expressed by sagittal diagrams, graphs, tables, and other forms (Klir and Yuan, 1995).

Basic mathematical operations can be performed on binary relations, such as the inverse and composition, and fuzzy set operations apply to binary relations such as the complement, union, and intersection. A fuzzy binary relation can be represented by a matrix, with the values of the matrix representing the values of the membership grades between sets. The fuzzy relation allows for partial membership as opposed to the crisp binary relation, which only allows for values of **0** or **1**, or in other words, either the presence or absence of association (Klir et al., 1998).

2.4.1. Composition Operations

A composition operation can be used to relate two binary relations producing a third binary relation. The two sets are related through their respective relationships to a third and common set. For example, the binary relation $P(X,Y)$ and $Q(Y,Z)$ have the common set Y, and the standard composition of these relations, denoted by $P(X,Y) \circ Q(Y,Z)$, produces the binary relation $R(X,Z)$ (Klir and Yuan, 1995).

There exist several possible composition operations. The most common are the maximum-minimum (max-min) composition, the maximum-product (max-product) composition, the sum-product composition, and the cumulative-minimum (cum-min) composition.

Max-Min

The max-min operation is represented by the following notation:

$$R(x,z) = \max \; \min \, [P(x,y), Q(y,z)] \qquad (2\text{-}1)$$

The max-min composition operation indicates the strength of the relational chain between x and z based on their membership grade. The basis for this operation is that "the strength of each chain equals the strength of its weakest link; the strength of the relation equals the strength of the strongest chain" (Russell and Fayek, 1994). The max-min composition determines the most likely solution based on the strongest indicator. The author finds this method to be unrepresentative of the entire data set since it only takes into account the maximum values in a link to take as the solution and simply discards the rest. This would therefore give a solution that is potentially overly cautious or overly risky.

Max-Product and Sum-Product

The max-product and sum-product operations are similar to the max-min operation, but Bourke and Fisher (1998) claim that in certain situations the max-product composition gives better results than the max-min composition. The max-min operation is applicable when the "intersection connector acts non-interactively", but when the connector is interactive, another solution, such as the product connector, may be more applicable. Therefore, if the concepts described by the sets in the binary relation interact, then the max-product and sum-product methods are preferable. Otherwise, the max-min technique is more suitable.

The max-product operation can be represented by the following notation:

$$R(x,z) = \max\,[P(x,y) * Q(y,z)] \qquad (2\text{-}2)$$

The sum-product is similar but in replace of taking the maximum value it uses the algebraic sum of the values. These operations will not be used as the factors in the model proposed in this thesis are independent. These techniques therefore are not suitable.

Cum-Min

The cum-min operation was introduced by Russell and Fayek (1994) and Fayek (1998). This operation accounts for other information as opposed to just taking the maximum. "The strength of each chain equals the strength of its weakest link, and the strength of the relation equals the summation of the strength of all chains" (Fayek, 1998). It takes into account each indicator, attribute, factor, etc. that points to the output value and increases the strength with which that output value is recommended. This method takes into account all ratings for a factor. A sensitivity analysis will be done in a further chapter to compare this method with the max-min operation.

2.4.2. Defuzzification

The step of defuzzification is used to convert the fuzzy set obtained from the composition operation into a crisp, real number output. It is important that the crisp number output best represent the fuzzy set. There are several defuzzification methods available, but only the most common methods will be reviewed. The methods that are the most common are the center of area method (also known as the center of gravity method or centroid method), center of maxima method, largest of maxima, smallest of maxima, and the mean of maxima method. These methods are discussed by Klir and Yuan (1995), Klir et al. (1998), Berenji (1992), and Pedrycz and Gomide (1998). An article by Van Leekwijck and Kerre (1999) develops a set of criteria for defuzzification and places the different defuzzification methods into classifications of maxima methods, distribution methods, and area methods.

Center of Area (COA)

The center of area method is the most common method of defuzzification. It determines the center of gravity of the area under the membership function. The equation for centre of area takes the membership value times each element divided by the sum of the membership values. The equation for center of area is:

$$A^* = \frac{\sum_{x\,\min}^{x\,\max} x \cdot A(x)}{\sum_{x\,\min}^{x\,\max} A(x)} \qquad (2\text{-}3)$$

Where A^* = the crisp defuzzified output

x = element

$A(x)$ = the membership value of element x

Middle of Maxima (MOM), Largest of Maxima (LOM), Smallest of Maxima (SOM)

These methods simply take the range of elements with the largest membership value and determine the middle value, largest value, and smallest value for the MOM, LOM, and SOM respectively as shown in figure 2.1. These methods are not as accurate and provide a rougher estimation of the defuzzified value then the centre of area method.

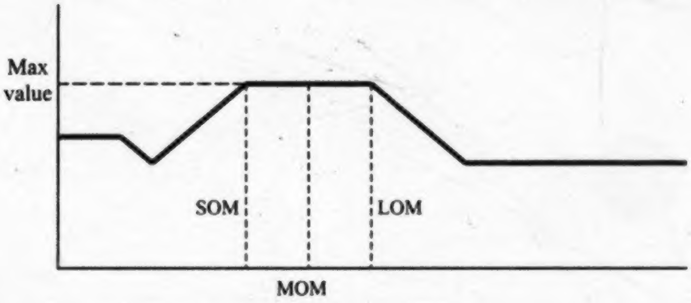


Figure 2.1 Representation of SOM, MOM and LOM

Mean of Maxima

The mean of maxima method is similar to the above methods, but slightly more refined. It takes the average value of all points whose membership value is equivalent to the maximum value to present as the crisp output. This method is acceptable but only takes into account the values with maximum membership instead of all values like the centre of area method does.

2.5 Summary

Little work has been done on modeling the problem of cost overruns and underruns during the design phase of construction. On the other hand, there has been plenty of research done on cost overruns during construction. A reason for this discrepancy may be because the profits made by contractors during construction are often much less than the profits made by consultants during design, which are quite arbitrary in most cases. Since there is little profit during construction, there is little room for error. But consulting is a business operation and all business operations strive to achieve the best quality output as well as the best profit.

Factors that affect design costs have been identified, examined, and studied in many cases but there is yet a model that combines these factors to show their cumulative effect on a project.

The use of fuzzy logic in construction and other areas is growing rapidly to become one of the most invaluable modeling techniques available. Its applicability to numerous areas of research from medical fields, to electrical controllers, to construction is astounding. Fuzzy set theory is an excellent tool for construction because of its mathematical simplicity and data requirements. Vast quantities of data are hard to come by on a construction site and most factors dealing with construction management cannot be represented by hard numbers, but are better represented by subjective ratings and linguistic values as needed in fuzzy modeling.

It is for these reasons that fuzzy set theory and fuzzy logic have been chosen to develop a model to predict design cost overruns and underruns for engineering consultants. The techniques reviewed here are for use with fuzzy binary relations. Later in this thesis, these techniques will be implemented in the model.

3. A Model to Predict Project Design Cost Overruns

3.1 Introduction

This chapter describes the model for predicting cost overruns and underruns on the design phase of a construction project. It is a general model that encompasses over twenty factors that affect overall design costs. In this model, the cost for the design includes both the cost associated with the design phase and the cost associated with the consultant's duties during the bidding, construction and warranty phases as well. The design phase considered is relative to the consulting engineers, whom are typically hired after the owner has determined the project requirements and the scope of work for the consultant should be defined. Figure 3.1 shows a flow chart of the design and construction process. In accordance with this flow chart, a consultant's duties begin at the time that the design team is hired and proceed throughout the rest of the process. The duties of the consultant during each phase may vary from project to project depending on the scope of work agreed to in the consultant's contract.

The fee for a project is originally determined during the call for proposals or in the fee proposal submission. The fee is typically determined in one of two ways: either as a percentage fee of the project budget; or based on the consultant's estimate of how much the work will cost. This fee may change throughout the project through negotiating with the client, as the scope of work changes or as the project becomes more defined. On percentage fee based projects, the fee is typically between 5-10% of the total project cost for the structural, mechanical and electrical consultants.

Estimating an accurate project fee is not an easy task for a consultant. To develop an estimate, the project manager must determine the number of hours required to perform the work and the hourly rate of work. APEGGA and AAA have produced a guideline entitled *Recommended Conditions of Engagement and Schedule of Professional Fees for Building Projects* (1998) that suggests payroll factor multipliers to determine the hourly rate of work that includes overheads and profit. Companies will often modify these factors to produce their own rate tables to specifically cover their profit and company overheads to use when estimating. Another common practice among project managers is to use their experience on similar jobs to determine the appropriate fee for the work. Estimating in the design industry is still very imprecise, and thus very inaccurate at times.

Commercial building projects for design consultants typically use a fixed fee contract, based on the fee proposal prepared by the consultant as discussed above, or a percentage fee contract, also discussed above. The fixed fee and percentage fee are both essentially a maximum upset price, meaning that the owner will pay the consultant the stipulated amount for the work. Additional costs or compensation for extra work or changes in scope are negotiated between the owner or prime consultant and consultant and evaluated on an individual basis.

Invoicing by the consultant to the owner or prime consultant is typically done on a milestone basis. Each milestone is awarded a percentage value of the total contract, and the consultant is paid upon completion of that milestone. A simple example of the milestones and percentages is:

• Conceptual design	30%
• Working drawings (include 30%, 60% and 90% review)	50%
• Construction phase	20%

Invoicing is done based on the companies billing period (typically 4 weeks or 1 month), where the partial completion of a milestone is estimated and the owner is billed accordingly (e.g. 50% completion of the conceptual design would equal a payment of 15% of the contract value), or an invoice is sent upon completion of a milestone. There should be minimum of one invoice per billing period. The milestones should be determined during contract negotiations between the consultant and owner or prime consultant, prior to commencing work on the project.

A cost overrun occurs when the actual cost of the work to the consultant exceeds the predetermined project fee that is paid by the owner or prime consultant to the consultant. Likewise, an underrun occurs when the consultant's actual cost is under the fee paid for completion of the work.

The model proposed in this chapter has three potential benefits to the industry:

1. It is a start to addressing the topic of cost control in design, which is currently at a very preliminary stage. There is potential for future research on this topic that may be much more encompassing than this research.
2. It will single out the factors that have the largest and most frequent impacts on design projects.
3. It identifies the risks on a project, based on the ratings given, to help a project manager decide if the project is too risky to pursue.

This chapter describes the factors used in the model, the framework of the model, the use of fuzzy set theory in the model, a sample project, and the applications of the model.

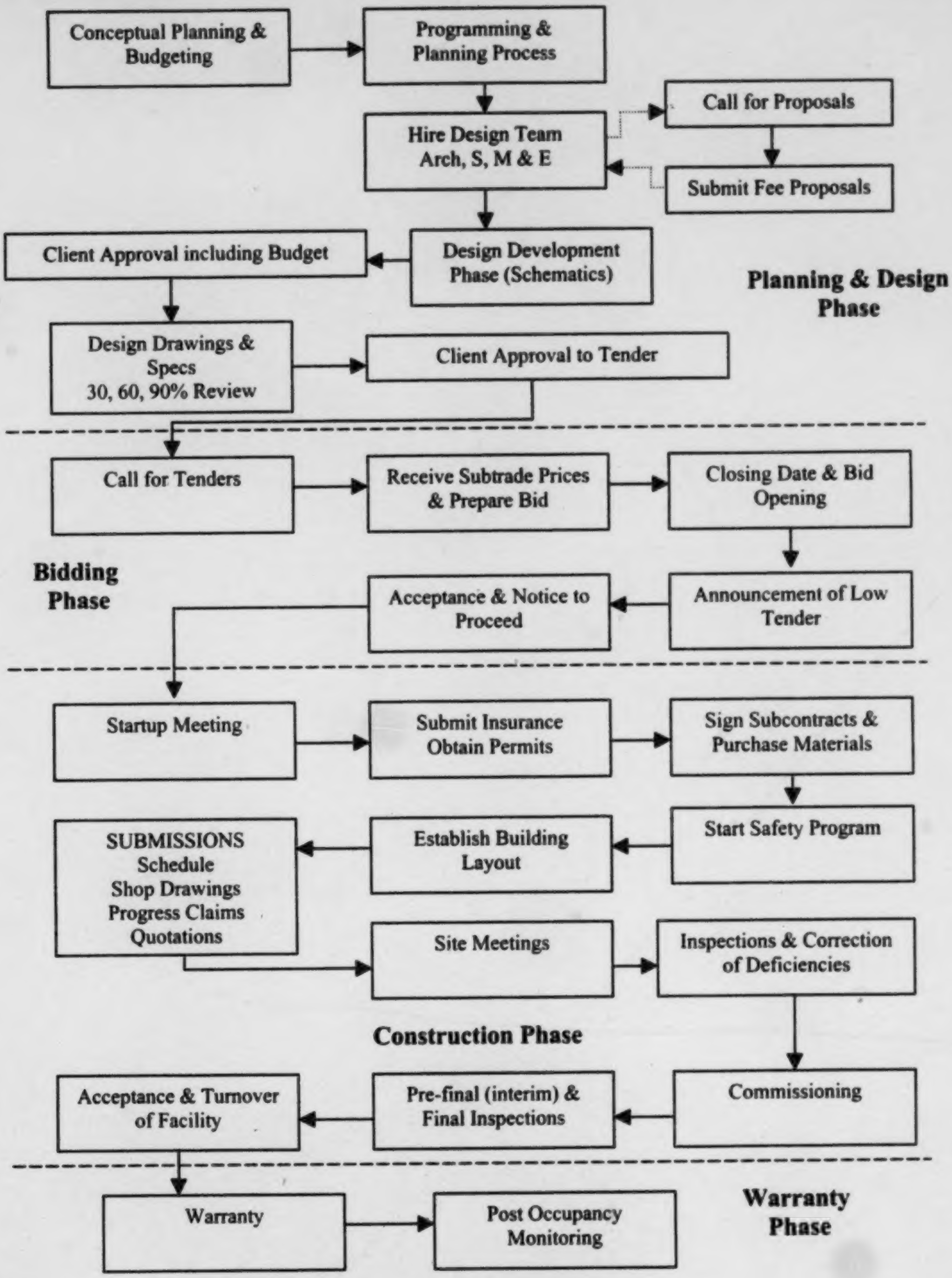

Conceptual Planning & Budgeting
Programming & Planning Process
Hire Design Team Arch, S, M & E
Call for Proposals
Submit Fee Proposals
Client Approval including Budget
Design Development Phase (Schematics)
Planning & Design Phase
Design Drawings & Specs 30, 60, 90% Review
Client Approval to Tender
Call for Tenders
Receive Subtrade Prices & Prepare Bid
Closing Date & Bid Opening
Bidding Phase
Acceptance & Notice to Proceed
Announcement of Low Tender
Startup Meeting
Submit Insurance Obtain Permits
Sign Subcontracts & Purchase Materials
SUBMISSIONS
Schedule
Shop Drawings
Progress Claims
Quotations
Establish Building Layout
Start Safety Program
Site Meetings
Inspections & Correction of Deficiencies
Construction Phase
Acceptance & Turnover of Facility
Pre-final (interim) & Final Inspections
Commissioning
Warranty
Post Occupancy Monitoring
Warranty Phase

Figure 3.1 Design and Construction Process

3.2 Project Characteristics that Affect Design Costs

There are many project characteristics that will ultimately affect the costs of a project, both in a negative way and in a positive way. For this research, the project characteristics that are most recognizable in their effect on project costs, and the project characteristics that potentially have the greatest effect on the project costs are chosen. The characteristics were identified through literature and by working with an engineering consultant to gain an expert opinion on what characteristics cause problems on their projects. A list of other project characteristics not used here is in Appendix C.

The following thirteen project characteristics were chosen for use in the proposed model:

1.0 Willingness of the prime consultant to approach the owner for extra fees.

2.0 Time taken by the owner/prime consultant/architect/engineer to make decisions.

3.0 Knowledge base of the owner.

4.0 Level of project scope definition between the consultant and the owner/prime consultant at the proposal stage.

5.0 Definition of scope duties passed on by the consultant's project manager to the design team.

6.0 Experience of the consultant's project manager.

7.0 Experience of the prime consultant's project lead.

8.0 Skill set of the consultant's design team.

9.0 Skill set of the architect's/engineer's design team.

10.0 Experience of the project team with similar projects.

11.0 Project complexity.

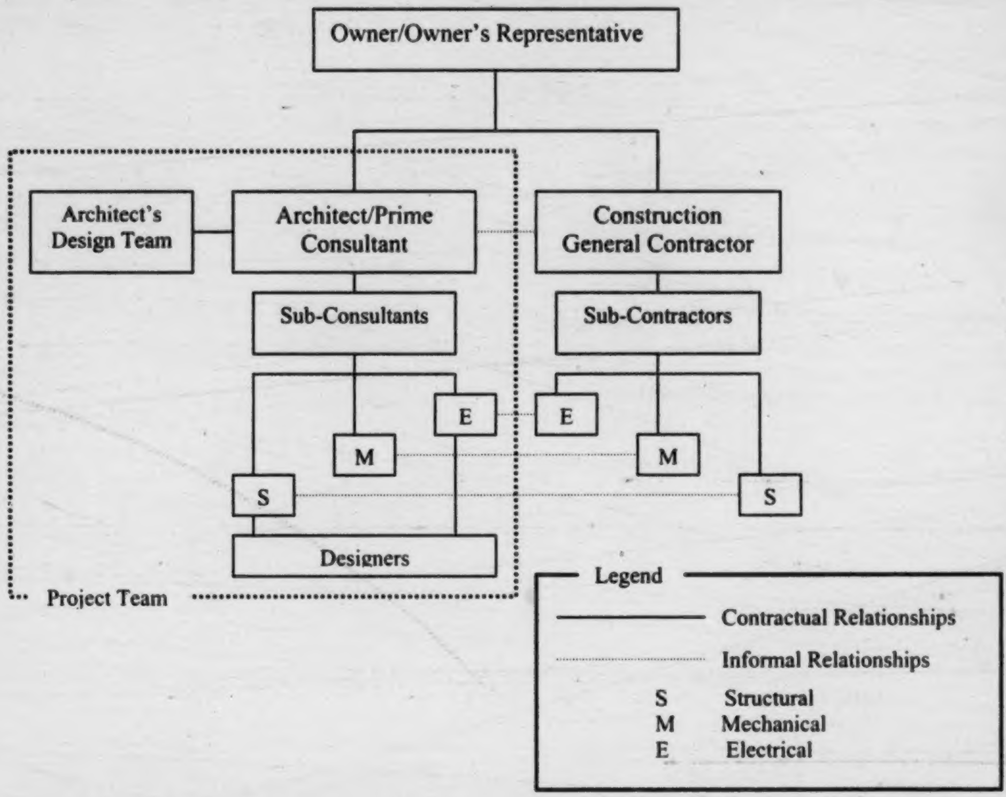
12.0 Timeline for design and construction.

13.0 Project location.

The prime consultant on a project is the party that reports to the owner or the owner's representative. The prime consultant may be the architect, and in that case these terms can be used interchangeably. However, there are projects were the architect is not the prime consultant and the terms represent separate parties. The consultant refers to the party that reports to the prime consultant; they may also be referred to as the subconsultant. For this model, the consultant will be the structural, mechanical, or electrical designer on the project. The project team refers to all parties involved in the project (i.e. architects, designers, engineers, etc.), and the design team refers to just the design staff of the mentioned party. These relationships can be seen in Figure 3.2.

The willingness of the prime consultant to approach the owner for extra fees is a relevant factor because this will dictate whether or not the consultant will get extra fees when the work is beyond the original scope or when changes or errors have been made by other members of the project team. Often if the prime consultant must also do extra work, he will then approach the owner, but if he is not affected then the consultant must absorb the extra costs.

Time taken to make decisions by the owner, prime consultant, architect, or engineers has an obvious effect on the schedule of work. Delays in the work will often lead to cost overruns, especially if employees are then required to work overtime in order to make deadlines.


Owner/Owner's Representative
Architect's Design Team
Architect/Prime Consultant
Construction General Contractor
Sub-Consultants
Sub-Contractors
E
E
M
M
S
S
Designers
Project Team
Legend
Contractual Relationships
Informal Relationships
S Structural
M Mechanical
E Electrical

Note: The project team will also include the construction contractor after that contract has been awarded. There may also be other parties involved (such as other specialist consultants and subcontractors), this diagram just includes those that are relevant to this research.

Figure 3.2 Organizational chart for a typical construction project

The knowledge base of the owner refers to the owner's knowledge of and previous experience with construction projects. If an owner has little construction knowledge he may not be aware of the impacts his decisions may have, he may not realize the impact of not making timely decisions, he may be more likely to make changes late in the project not realizing the cost impacts, and more time may be required to explain matters to the owner. It is said that owners with no construction experience and owners with very high construction knowledge are the best to work with. Those with no experience will allow the project team to take charge of the project, whereas owners with some experience want to be more involved but are more of a hindrance than a help to the project.

The level of scope definition between the consultant and the owner/prime consultant can be measured based on the Project Definition Rating Index (PDRI) for Building Projects produced by the Construction Industry Institute (2000). The PDRI provides a list of potential scope of work items that are ranked as to their importance to the project. A project manager can go through the list and rate the definition of the items for a specific project on a scale of 0 to 5. The total score provides an indicator as to how well defined the scope is. The scope of work items have been tailored to suit the work of the cooperating company (see Appendix A). However, the PDRI rating was not used for data collection because it proved unrealistic to expect one to recall exact information available at the beginning of a past project. Factor 5.0, the definition of scope duties within the consultant's design team is a ranking of how well the work was communicated from the project manager to the design team.

The experience of the consultant's project manager and of the prime consultant's project lead are important because typically those with more experience are more efficient, possibly more capable, may have better knowledge on how to deal with problems that arise, and may have better managerial skills for leading the project. The same applies for the experience of the project team with similar projects. People can be more efficient in dealing with situations they have dealt with before. The skill set of the architect's and consultant's design teams affects productivity, efficiency, and accuracy of the drawings.

The project complexity is ranked according to the APEGGA Recommended Conditions of Engagement and Schedule of Professional Fees for Building Projects (1998). APEGGA provides seven categories of buildings of increasing complexity. These categories have been amended to suit the business and skills of the cooperating company (see Appendix B) as it was found that the APEGGA ratings were out of date in terms of the technological complexity of buildings.

The timeline of the project, including both the design phase and the construction phase, can have an affect if the timeline is too short or if it is too long. A timeline that is too short can cause an unrealistic schedule. This may force people to hurry through the work, perhaps causing them to do a less thorough a job, and creating more room for errors and omissions in the designs. The same applies for the construction phase. It can also create an unhealthy atmosphere throughout the project, causing breakdowns in communication and impeding people's ability to work together. If the timeline is too long, the work may be put off in order to complete more immediate tasks and the project will have a greater possibility of being cancelled altogether.

The ideal project location is within the local vicinity; more remote projects are more prone to problems. On a remote project the project managers do not have as much opportunity to visit the site and are more often dealing with foreign contractors and other parties that they have not dealt with on previous projects.

These project characteristics on their own may not necessarily create cost overruns or savings, but coupled with the following risk events they are certain to have an impact on the project.

3.3 Risk Events that Affect Design Costs

Risk events are undesirable or fortuitous events that occur during the design and construction phases of a project, possibly leading to a cost overrun or savings. Risk should always be taken into account on a project, but due to the competitive nature of the industry not every possible risk event can be accounted for in the project fee. This puts the onus on the consultant and the contractor to deal with, and possibly cover the cost of, both negative and positive risk events. There are many events that can affect the outcome of a project; here 8 have been selected as being the most common or having the largest impact on projects. Again these factors have been chosen from the literature reviewed and with help from an engineering consultant to provide an expert point of view. Appendix C contains a list of other risk events not used here. The risk events considered are:

I. Accuracy of site investigation.
II. Design errors or omissions.
III. Design/scope changes by the owner, consultants or architect.
IV. Communication amongst the project team.
V. Over-engineering.
VI. Constructability issues.
VII. Inadequate design team resources.
VIII. Adequacy of the general contractor and subcontractors.

Each of these risk events can have either a positive or negative impact on the project. For example, if the soil conditions are worse than determined during the site investigation, it may cost extra for construction and/or for redesign. But if the conditions are more favourable, it may result in a cost savings.

The risk factors are all fairly obvious as to the problems they can create. An inaccurate site investigation can cause numerous design changes. The problem would most likely not be noticed until construction starts, which would mean the design is complete or near completion, and the design may need to be amended to suit the change in conditions. Extra costs incurred by this problem may or may not be compensated for by the owner.

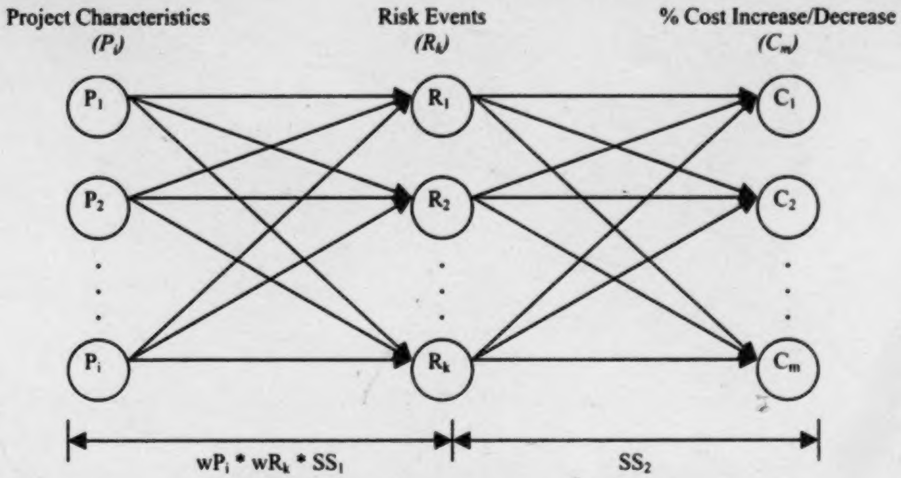
Design errors by one's own design team and others on the project team may create the need for rework. In this case, the owner will typically not compensate the consultant for the cost of the extra work as it is the fault of the design team.

Scope and design changes by the owner, architect, or other consultants may or may not be compensated for depending on the situation. An owner induced change will typically be compensated for, but if another member of the design team makes a change to an existing design for whatever reason and it affects the other designer's work, this will most likely not be compensated for. The willingness of the prime consultant to approach the owner for extra fees will play a big role in whether or not one is compensated for these changes.

Poor communication amongst the project team can cause coordination problems, misunderstandings, and delays to the work among other things. Over-engineering is typically an internal problem that results in higher then expected labour costs and possibly construction costs. Constructability issues may cause rework after design completion, if the structure cannot be built the way it was designed. Inadequate design team resources, also an internal issue within a consulting firm, is caused when the designers and project staff with the desired skill levels are unavailable for the project. The result could be either too much work for the team to handle, or unqualified people working on the job. The general contractor and subcontractors can have an impact on the designers' work and responsibilities during the construction phase of the project. Typically if the contractor is inadequate to handle the job this will affect the entire project and project team. These risk events are all problems that will not be compensated for by the owner, as they are either the consultant's or project team's fault or responsibility.

3.4 Structure of the Model

The model uses the above project characteristics and risk events to predict design cost overruns. Binary relations are used to relate the project characteristics to the risk events, and the risk events to the percentage cost overrun, above the contract fee, which is the output. The structure of the model is displayed in Figure 3.3. The project characteristics are related to the risk events by a standard strength SS_l. This standard strength represents the sensitivity of the impact of the risk event to variations in the project characteristic. For example, if risk event R occurs to the worst degree possible, how strong is its impact on the project cost, based on the degree of existence of project characteristic P. The cost impact of the risk event, then, is dependent on the degree to which the project characteristic exists. The standard strength is hard-coded into the model. It is determined based on expert opinion. The process by which the expert opinions were solicited is described in Chapter 4.



Where

SS_1 = Standard strength between the project characteristics and the risk events.
- Hard-coded into the system, pre-defined by expert opinion.
- These standard strengths represent the strength of the impact on the cost from risk event R_k occurring with variations in the project characteristic P_i.

SS_2 = Standard strength between the risk events and the cost increase/decrease.
- Hard-coded into the system, pre-defined by expert opinion.
- These standard strengths represent the likelihood of each cost range occurring.

wP_i = Project characteristic strength
- User defined for a specific project.
- The strength (wP_i) represents the degree to which this characteristic existed for the specific project.

wR_k = Risk event strength
- User defined for a specific project.
- The strength (wR_k) represents the extent to which this risk event occurred on this project and the extent of its impact.

C_m = Cost increase/decrease (%) above the contract fee.
- Ranges decided by expert opinion.
- The range of percent increase/decrease that will result from project characteristics and risk events occurring simultaneously at different levels.

Figure 3.3 Model for predicting design cost overruns

The project characteristics, P_i, and risk events, R_k, are considered independent in this model. The model does not use the probability that a risk event will occur given a certain project characteristic, but instead input decrees that project characteristic *P* exists to degree *n*, and risk event *R* occurred to extent *m*. Dealing with probabilities and predicting the occurrence of events is a completely different model then the one proposed here.

The degree of existence of the project characteristics and the degree of occurrence of the risk events are given ratings between **0** and **1** that are input by the user. For the project characteristics, a rating of **0** indicates *poor*, and a rating of **1** is an *excellent* rating. Likewise for the risk events, a **0** represents the *worst case* where large problems resulted from the risk event, and **1** represents the *best case* where the risk event caused a possible cost savings. For both scales, a rating of **0.5** indicates that the project characteristic or risk event had a *neutral* effect on the project. Neutral would signify that the factor existed or occurred in a state that is typical and expected of projects. Since there is no such thing as an ideal or perfect project, all factors are rated relative to what is normally expected to occur on a project. This is then relative to the expectations of the project managers and the company dealt with for data collection. The ratings between **0** and **1** represent fuzzy membership values that represent the user's subjective assessment.

A percent cost overrun or underrun, C_m, is the resultant of each combination of project characteristic and risk event. This percentage is the expected cost overrun, above the contract fee, given that the project characteristic exists to the worst degree possible and the risk event occurs to the worst degree. Or, for a best-case scenario, the percentage is the expected cost underrun, below the contract fee, given that the project characteristic exists to the best degree possible and the risk event occurs to the best degree.

The second standard strength, or SS_2, represents the strength between each risk event, R_k, and cost range, C_m. The cost range that was identified as the most likely cost overrun or underrun given a worst-case or best-case scenario, receives a strength of 1.0.

The neighbouring cost ranges receive strengths decreasing outwardly in increments of 0.2. The most likely percent cost range is decided by expert opinion, as with the first set of standard strengths, and hard-coded into the model.

3.5 Use of Fuzzy Set Theory in the Model

Fuzzy set theory, as described in Chapter 2, was introduced by Zadeh in 1965. Fuzzy set theory is a method of reasoning with linguistic variables and subjective assessments. Fuzzy set theory was chosen for use in this model for two reasons:

1. Due to a lack of quantitative data on the subject, it was necessary to use subjective judgments and expert opinions in order to create input for the model and develop reasoning within the model.
2. To expand the uses of fuzzy set theory in the construction industry.

A binary relation is used to approximate the relationship between two data sets given the degree of association between the sets, as discussed in Chapter 2. For this model, we are using binary relations to predict the percent cost overrun or underrun given the existence of certain project characteristics and the occurrence of certain risk events.

The first binary relation formed is between the project characteristics and risk events, called the $S(P,R)$ relation. This relation takes into account the ratings given to the factors by the user. The $S(P,R)$ relation is calculated by the following formula:

$$S(P,R) = wP_i * wR_k * SS_{1ik} \tag{3-1}$$

Where

$S(P,R)$ = the fuzzy binary relation between the project characteristics and risk events, from 0.0 to 1.0

wP_i = the rating of project characteristic *i*, from 0.0 to 1.0

wR_k = the rating of risk event *k*, from 0.0 to 1.0

SS_{Iik} = the standard strength between project characteristic *i* and risk event *k*, from 0.0 to 1.0

As mentioned in the previous section, the standard strength between the project characteristics and risk events represents the sensitivity of the cost impact of the risk event to variations in the existence of the project characteristic.

The second binary relation, the *F(R,C)* relation, relates the project characteristics and risk events to percentage cost overruns/underruns. For each combination of project characteristic and risk event, a most likely range of percentage cost overrun and underrun has been identified through expert opinion. The ranges of cost overruns and underruns used are shown in Table 3.1.

Table 3.1 Ranges of cost overruns and underruns

	Cost Range	Linguistic Descriptor
C_0	-50% to -20%	VERY HIGH
C_1	-20% to -10%	HIGH
C_2	-10% to -5%	MEDIUM
C_3	-5% to 0%	LOW
C_4	0%	ZERO
C_5	0% to 5%	LOW
C_6	5% to 10%	MEDIUM
C_7	10% to 20%	HIGH
C_8	20% to 100%	VERY HIGH

These ranges were identified by expert opinion as being LOW, MEDIUM, HIGH and VERY HIGH cost overruns and underruns as indicated. The maximum and minimum values for the underruns and overruns were chosen based on the data collected from actual projects.

The membership values, or standard strengths, for this matrix are values decreasing outwardly by increments of 0.2 starting with a value of 1.0 for the percentage range identified as the most likely cost overrun for that combination of factors. For example, if C_2 receives a value of **1.0**, then C_1 and C_3 receive a value of **0.8**, C_0 and C_4 receive a value of **0.6**, all the way down to a value of **0**, or until the end of the matrix is met. These incremental values give the decreasing likelihood of the cost ranges occurring. It accounts for the fact that the chosen cost range may be the most likely to occur, but the other ranges may also occur but with less likelihood. This is one of the advantages of using fuzzy logic.

Once these two binary relations are formed, they are combined to produce a third binary relation using the composition operation. This operation yields the fuzzy binary relation $Q(P,C)$, which relates the project characteristics to the percent overrun/underrun through their respective relationship to the risk events. There are two types of composition operations that will be used and compared; the maximum-minimum composition operation and the cumulative-minimum composition operation. Both are discussed in Chapter 2, their accuracy is compared in Chapter 5.

After the composition operation is used to combine the $S(P,R)$ and the $F(R,C)$ relations to obtain the $Q(P,C)$ relation, the total strength of each percentage range is calculated using (3-2). This formula takes the sum of the strengths for each percentage range, and divides the sum by the total of the project characteristic ratings. This operation for combining the strengths is analogous to the statistical concept of weighted means (Berenji, 1992). The 'strengths' are the membership values of the *Q(P,C)* relation for each percentage range. The highest strength points to the most likely range of percent cost overrun/underrun based on the standard strengths within the model and the user input ratings for the project characteristics and risk events.

$$Q(P,C_m) = \frac{\sum_{n=1}^{i} Q(P_n,C_m)}{\sum_{n=1}^{i} wP_n} \tag{3-2}$$

Where

$Q(P,C_m)$ = the total strength of cost range C_m

$\Sigma Q(P_n,C_m)$ = the sum of the membership values for each C_m element from the $Q(P,C)$ relation

ΣwP_n = the sum of the user input project characteristic ratings

The membership function in Figure 3.4 shows a sample output of the model, which can now be defuzzified to obtain a single (crisp) value if desired. Defuzzification looks at the strength for each percentage range and finds the most likely cost percentage either by calculating the area under the curve using the centre of area method, or simply by examining the percentage range with the highest strength (the mean of maximum, LOM, SOM, and MOM methods). The center of area method takes the centroid, or midpoint, of each range and multiplies it by its membership value, then divides by the sum of the membership values. The values for LOM, SOM, and MOM are the largest, smallest and middle values of the range with the highest membership value, as shown in Figure 3.4. These defuzzification methods are discussed in greater detail in Chapter 2. The output of the model is a single, crisp defuzzified number.

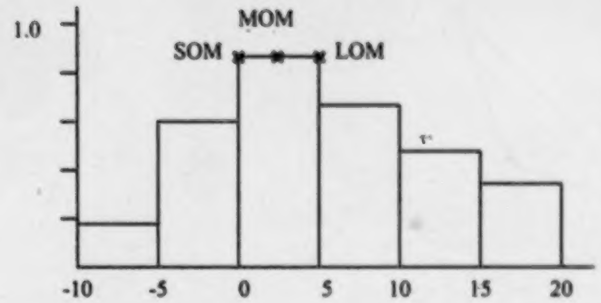


Figure 3.4 Fuzzified output of the model (Note: the percentage ranges do not accurately reflect those used in the model)

3.5.1. Accounting for Cost Overruns and Underruns

Although the primary goal of this research is to predict cost overruns from the project characteristics and risk events on a project, potential cost underruns must also be taken into account. When identifying the standard strengths for the model, a worst-case scenario approach is used so that when the input ratings for the existence and occurrence of the factors were entered, it scales down the output to approximate the actual result. In using this worst-case scenario approach, potential cost underruns are not accounted for. Therefore, a best-case scenario with standard strengths is also provided for the model. The calculation for the predicted cost overrun/underrun is actually determined through two models; the first is a 'worst-case' model, and the second a 'best-case' model.

The two models are identical, except each has its own standard strengths representing the degree of sensitivity of the impacts of the risk events to variations in the project characteristics, and the expected cost overrun or underrun. Therefore one model will predict cost overruns and the other will predict cost underruns based on the same user input. The 'best-case' and the 'worst-case' model are joined after the composition operation by summing the membership values in the $Q(P,C)$ relation.

The necessity for the two models is because the standard strengths between the project characteristics and the risk events are different for the best-case scenario and the worst-case scenario. This means that a risk event may be impacted differently by a project characteristic during a negative situation versus a positive situation. When compiling a fee proposal, in order to stay competitive and win jobs, project managers assume that a project will run smoothly. The project characteristics on their own have potential to create impacts on cost, but when they are coupled with worst-case risk events, the potential impact can be much greater. On the other hand, the impact from project characteristics does not change much when coupled with best-case risk events because the best-case scenario is almost expected when bidding. The ratings for the factors are therefore run through both the 'best-case' model and the 'worst-case' model and combined to produce the percent cost increase or decrease.

The ratings of the factors for the 'best-case' model are simply the inverse of the ratings of the 'worst-case' model. For example, if the experience of the consultant's project manager has a membership value of **0.2** in *poor*, then it has a membership value of **0.8** in *excellent*. A 1:1 relationship exists between the rating and the membership value, μ. This is demonstrated by the membership function in Figure 3.5.

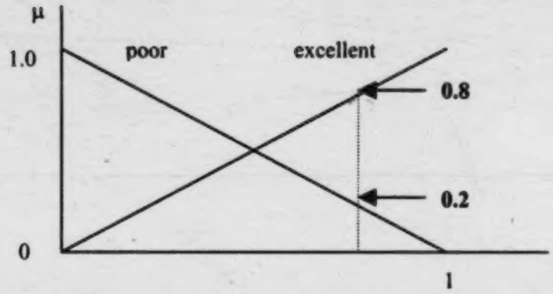


Figure 3.5 Membership function for the experience of the consultant's project manager

It is important to note that the 'best-case' and the 'worst-case' model do not cancel each other out in any way. The strength of the relationships between the factors and their impact is much greater for the 'worst-case' model then for the 'best-case'. In a cost overrun scenario, the strength of the membership values of the cost underrun percentages will be quite minimal and will not have significant impact on the defuzzified output, and likewise for a cost underrun scenario where the cost overrun percentages will have a minimal impact. The effect of the two models together will produce a slightly more conservative prediction.

3.5.2. Sample Project

The following sample project is used to illustrate the calculations performed in the model. For the sample project, the full range of factors is not used in order to simplify the calculations and reduce the size of the matrices. Three project characteristics will be used, **1**, **2**, and **3**, and three risk events, **A**, **B**, and **C**. The calculations on the left will be for the 'worst-case' model, and the calculations on the right will be for the 'best-case' model, until the models are joined to produce the combined output. Two methods of the composition operation will be shown: the max-min composition operation and the cum-min composition operation.

Step 1:

- **Identify the user input ratings for the project characteristics and risk events.**

WORST-CASE

Project Characteristics, P_i	Degree of Existence, wP_i
1	0.8
2	1.0
3	0.4
ΣwP_i	2.2

Risk Events, R_k	Degree of Occurrence, wR_k
A	0.4
B	0.9
C	0.5

BEST-CASE

Project Characteristics, P_i	Degree of Existence, wP_i
1	0.2
2	0
3	0.6
ΣwP_i	0.8

Risk Events, R_k	Degree of Occurrence, wR_k
A	0.6
B	0.1
C	0.5

Step 2:

- **Identify the standard strengths between the project characteristics and risk events and between the risk events and the cost ranges.**

	SS_1	SS_2
1A	1.0	C_9
1B	0.8	C_7
1C	0.9	C_9
2A	0.4	C_6
2B	0.5	C_7
2C	0.9	C_{10}
3A	0.3	C_6
3B	0.6	C_8
3C	0.7	C_7

	SS_1	SS_2
1A	0.6	C_2
1B	0.5	C_3
1C	0.5	C_3
2A	0.8	C_1
2B	0.3	C_4
2C	0.4	C_2
3A	0.2	C_3
3B	0.1	C_4
3C	0.1	C_5

- **The cost ranges are:**

C_6 = 0%
C_7 = 0% to 5%
C_8 = 5% to 10%
C_9 = 10% to 20%
C_{10} = 20% to 35%

C_1 = -20% to -35%
C_2 = -10% to -20%
C_3 = -5% to -10%
C_4 = 0% to -5%
C_5 = 0%

Step 3:

- **Calculate the values of the *S(P,R)* relation.**

S(P,R)	A	B	C
1	0.32	0.58	0.36
2	0.16	0.45	0.45
3	0.05	0.22	0.14

S(P,R)	A	B	C
1	0.07	0.01	0.05
2	0.00	0.00	0.00
3	0.07	0.01	0.03

Sample Calculation:

$$S(P_i, R_k) = wP_i * wR_k * SS_{1ik}$$

$$S(P_1, R_A) = wP_1 * wR_A * SS_{11A}$$

$$= 0.8 * 0.1 * 1.0$$

$$= \mathbf{0.08}$$

Step 4:

- **Calculate the values of the *F(R,C)* relation.** (The most likely cost overrun/underrun receives a value of 1.0, the surrounding costs receive values decreasing outwardly be increments of 0.2.)

F(R,C)	C_6	C_7	C_8	C_9	C_{10}
1A	0.4	0.6	0.8	1.0	0.8
1B	0.4	0.6	0.8	1.0	0.8
1C	0.6	0.8	1.0	0.8	0.6
2A	1.0	0.8	0.6	0.4	0.2
2B	0.8	1.0	0.8	0.6	0.4
2C	0.2	0.4	0.6	0.8	1.0
3A	1.0	0.8	0.6	0.4	0.2
3B	0.6	0.8	1.0	0.8	0.6
3C	0.8	1.0	0.8	0.6	0.4

F(R,C)	C_1	C_2	C_3	C_4	C_5
1A	0.8	1.0	0.8	0.6	0.4
1B	0.6	0.8	1.0	0.8	0.6
1C	0.6	0.8	1.0	0.8	0.6
2A	1.0	0.8	0.6	0.4	0.2
2B	0.4	0.6	0.8	1.0	0.8
2C	0.8	1.0	0.8	0.6	0.4
3A	0.6	0.8	1.0	0.8	0.6
3B	0.4	0.6	0.8	1.0	0.8
3C	0.2	0.4	0.6	0.8	1.0

Step 5:

- **Apply the maximum-minimum composition operation to obtain the *Q(P,C)* relation.**

Q(P,C)	C_6	C_7	C_8	C_9	C_{10}
1	0.40	0.58	0.58	0.58	0.58
2	0.45	0.45	0.45	0.45	0.45
3	0.22	0.22	0.22	0.22	0.22
sum/Σ*wP*	0.48	0.56	0.56	0.56	0.56

Q(P,C)	C_1	C_2	C_3	C_4	C_5
1	0.07	0.07	0.07	0.07	0.07
2	0.00	0.00	0.00	0.00	0.00
3	0.07	0.07	0.07	0.07	0.07
sum/Σ*wP*	0.07	0.07	0.07	0.07	0.07

Sample Calculation:

$Q(P_i, C_m) = \text{max min } [S(P_i,R_k) , F(R_k,C_m)]$

$Q(P_1, C_6) = \text{max min } [(0.32,0.4), (0.58,0.4), (0.36,0.6)]$

$= \text{max } (0.32, 0.4, 0.36)$

$= \mathbf{0.40}$

- **Calculate the total strength of each cost range:**
  (The calculations are shown with the *Q(P,C)* matrix)

$= \Sigma C_m/\Sigma wP_i$

For C_6, the total strength $= (0.40 + 0.45 + 0.22) / 2.2$

$= \mathbf{0.48}$

- **Apply the cumulative-minimum composition operation to obtain the *Q(P,C)* relation.**

Q(P,C)	C_6	C_7	C_8	C_9	C_{10}
1	1.08	1.26	1.26	1.26	1.26
2	0.81	1.01	1.06	1.06	1.01
3	0.40	0.40	0.40	0.40	0.40
sum/Σ*wP*	1.04	1.21	1.24	1.24	1.21

Q(P,C)	C_1	C_2	C_3	C_4	C_5
1	0.13	0.13	0.13	0.13	0.13
2	0.00	0.00	0.00	0.00	0.00
3	0.11	0.11	0.11	0.11	0.11
sum/Σ*wP*	0.11	0.11	0.11	0.11	0.11

Sample Calculation:

$Q(P_i, C_m) = \text{sum min } [S(P_i,R_k), F(R_k,C_m)]$

$Q(P_1, C_6) = \text{sum min } [(0.32,0.4), (0.58,0.4), (0.36,0.6)]$

$= \text{sum } (0.32, 0.4, 0.36)$

$= \mathbf{1.08}$

- **Calculate the total strength of each cost range:**
  (The calculations are shown with the *Q(P,C)* matrix)

$= \Sigma C_m/\Sigma wP_i$

For C_6, the total strength $= (1.08 + 0.81 + 0.40) / 2.2$

$= \mathbf{1.04}$

Step 6:

- **Combine the 'best-case' and the 'worst-case' model by combining the strengths of each cost range calculated in the *Q(P,C)* relation, and normalize the values of the matrix. The values are normalized to prevent having recommendations greater than 1.0 and to ensure at least one recommendation equals 1.0.**
  - From the max-min composition operation:

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
	0.07	0.07	0.07	0.07	0.07	0.48	0.56	0.56	0.56	0.56
Normalized	0.12	0.12	0.12	0.12	0.12	0.86	1.00	1.00	1.00	1.00

  - From the cum-min composition operation:

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
	0.11	0.11	0.11	0.11	0.11	1.04	1.21	1.24	1.24	1.21
Normalized	0.09	0.09	0.09	0.09	0.09	0.84	0.98	1.00	1.00	0.98

Step 7:

- **Apply the centre of area method of defuzzification:**
  (This calculation would normally use an integral, but in this case taking the midpoint value of each range will produce the same solution)
  - From the max-min composition operation:

$$C^* = \frac{\Sigma C_m * wP_i}{\Sigma wP_i}$$

$$= [(-27.5\% \times 0.12) + (-15\% \times 0.12) + (-7.5\% \times 0.12) + (-2.5\% \times 0.12) + (0\% \times 0.12) + (0\% \times 0.86) + (2.5\% \times 1.00) + (7.5\% \times 1.00) + (15\% \times 1.00) + (27.5\% \times 1.00)] / (0.12+0.12+0.12+0.12+0.12+0.86+1+1+1+1)$$

$$= \mathbf{8.5\%}$$

  - From the cum-min composition operation:

$$C^* = \frac{\Sigma C_m * wP_i}{\Sigma wP_i}$$

$$= [(-27.5\% \times 0.09) + (-15\% \times 0.09) + (-7.5\% \times 0.09) + (-2.5\% \times 0.09) + (0\% \times 0.09) + (0\% \times 0.84) + (2.5\% \times 0.98) + (7.5\% \times 1.00) + (15\% \times 1.00) + (27.5\% \times 0.98)] / (0.09 + 0.09 + 0.09 + 0.09 + 0.09 + 0.84 + 0.98 + 1 + 1 + 0.98)$$

$$= \mathbf{9.0\%}$$

- **The output of this sample project predicts that the conditions of this project will cause an 8.5% cost overrun, above the contract fee, using the max-min composition operation; or a 9.0% cost overrun using the cum-min composition operation.**

3.6 Applications of the Model

This model is to be used by consulting engineers in the commercial construction sector. The data was gathered from design firm employees working in the disciplines of mechanical, structural, and electrical engineering. The project size can vary, but the model is most applicable to projects with an engineering fee in the $100,000 to $500,000 range. On smaller projects, slight cost increases will cause huge percent cost overruns because the percentage is relative to the size of the job. Therefore the model may not predict accurate results on smaller jobs of less than $50,000.

The model is to be used during the proposal stage of the project (i.e. as the consultant is preparing the fee estimate) or at the onset of the consultant's work on the project. At this stage, the majority of the project characteristics should be known factors. The exception may be if the user does not have any previous experience working with other members of the project team, such as the owner, architect, and other consultants, and is unable to judge their capabilities. At this stage the occurrences of risk events is obviously unknown, but they can be estimated based on the user's experience with similar jobs or based on the user's experience with the project team members.

The model is to be used for risk analysis or project awareness, and not as an estimating tool. The consultant's fee estimate should be complete at this point and the model will identify the sensitivity of the project to certain characteristics and risk factors. The process of entering ratings into the model will make the user more aware of the potential risks on the project and their impact in combination with the project characteristics. The process may also determine if the project is in fact too risky to pursue and the user may decide against putting in a fee proposal for the job or hi-balling the fee to cover the potential risks. The exercise of determining the level of scope definition will aid the user in further defining the scope of work if necessary, or suggest that the owner should be approached for further clarification on the project and the duties of the consultant.

The prediction of the model may help to reduce cost overruns if the warning is heeded. If a project manager is aware of some negative characteristics or potential risk events that will have an effect on the final cost of the job and what the cost impact may be, he or she may pay more attention to tracking costs throughout the project to keep them under control, or possibly look for areas where there is a potential for cost savings. The model can also be used mid-way through a project to check the potential impact of risk events that have occurred. This way the project manager will know ahead of time if there will be serious cost overruns as a result of the risk events.

3.7 Conclusion

This chapter explained and described the framework of the model. The project characteristics and risk events that are factors in the model are listed and the relevance of each factor is explained in context to its purpose in the model. The structure of the model shows how the project characteristics and risk events are used to predict the design cost overrun or underrun. The model uses fuzzy binary relations to relate the project characteristics and risk events and then calculates the cost overrun/underrun based on standard strengths hard-coded into the model. A sample project is given to demonstrate the use of fuzzy binary relations and step through the calculations. And finally, the appropriate situations for using the model, and the potential applications of the model are described.

The next chapter will cover the data collection process, provide the data for the model, and draw conclusions from the data regarding the most serious risk events and the most common project characteristics with negative impacts.

4. Data Collection and Results

4.1 Introduction

The data for this research was provided by a local Edmonton consulting engineering design firm. This company was targeted, as mentioned in Chapter 1, based on their reputation in the community, their involvement with the University of Alberta, the type of work they were typically involved in, the size of the company, and their willingness to contribute to construction research. The partnership was formed with mutual intent in that the company would provide the researcher with guidance and data, and in return would receive conclusions drawn from the data, access to the model, and a checklist of scope definition items. The identity of the design firm will remain anonymous and will herein be referred to as 'the Company'.

Two separate interview questionnaires were developed in order to acquire the necessary data for the model. The first interview is titled the 'expert interview' and its purpose is to determine the standard strengths used in the model. The second interview questionnaire was developed to collect the data necessary for testing the model.

This chapter will cover the development of the interview questionnaires that were used for data collection purposes, the interview methodologies, and the results of the data collection.

4.2 Development of the Interview Questionnaires

The questionnaires were developed with the aid of a project manager with the Company. The project manager was consulted for details on the financial aspects of projects, such as how project fees are established and the accounting systems of the Company. He was also the main force in identifying and simplifying the list of factors that were to be used in the model, and on the interview questionnaires. The researcher was briefed on certain ways in which costs are accounted for and things to look out for in order to obtain correct, pertinent data. For example, different rate tables can be used in the cost accounting system to track the costs charged to the job. These rates factor in company overheads, profit and other costs, and are multiplied by base salaries to obtain the charge-out rate for each employee billing hours to the job. The rates are used primarily internally within the cost accounting system to calculate the costs incurred on each project, but may also be used for estimating purposes. It is the calculated cost from the cost accounting system, which includes salaries, company overheads, profit and other costs, compared to the final amount billed that determines if there was a cost overrun or underrun on the job. The actual cost of the work, then, depends on the multiplier that was used to calculate labour rates. Another factor to watch out for was whether a 3% programming fee or a 2% financial management fee was included in the job costs. This is apparently a new development for the Company as none of the project managers were aware that these fees should be added to their projects.

Developing the interview questionnaires was an iterative process resulting in many meetings with the project manager. It was important to marry the practical inputs from the project manager with the data input needs of the chosen modeling technique. The project manager aided in developing questions that needed to be asked, and they were then formulated to elicit the correct type of responses from the interviewees needed for the model.

Once the first drafts of the project questionnaires were completed, they were passed on to another project manager within the Company for input. The suggested changes were incorporated and the questionnaires were finalized. The questionnaires are displayed in Appendix D and Appendix E.

4.3 Interview Methodology

Prior to commencing the interviews, an informal meeting was set up with all interview participants to introduce the project, introduce the researcher, cover what was expected from the participants, and ensure confidentiality of the information given. The meeting also assured the participants that there was approval from their superiors and they were encouraged to participate and freely divulge any financial information needed.

Approximately ten project managers attended the meeting. They were from the disciplines of electrical, mechanical, and structural engineering as well as an architect who was formerly a structural design engineer. From the attendees of this meeting, five were selected to participate as 'experts' in the expert interview. The rest, as well as the five 'experts', were to be interviewed for the project manager interview. The architect was used as an expert but not for the project manager interview. Although his insights were very helpful for the expert interview, the project manager interview required selecting recent projects and answering questions from a consulting engineer's point of view, which he was unable to do since all projects he is involved in are from an architectural standpoint.

4.3.1. Expert Interview

As mentioned in the previous section, the five 'experts' chosen to participate in the expert interview were selected from a group of project managers. An expert from each discipline was chosen, so the group was comprised of a structural engineer, two electrical engineers, a mechanical engineer, and a former structural engineer now working as an architect. The architect was an asset to the team because not only did he have previous consulting experience, he was able to provide extra insight from an architect's viewpoint on the factors concerning the architect and project team.

A panel approach was used for this expert interview where the five individuals meet to discuss and assign the standard strengths for the model. A collaboration to determine the data, as opposed to individual interviews, was preferred as it eliminated the need to statistically combine the individual responses.

The expert interview was conducted prior to the project manager interviews to allow for discussion of the chosen factors and decide if other factors should be added to the list. There were other factors suggested that affect project costs, such as whether the job is public or private and the project delivery method, but these factors were not incorporated into the model. The suggested factors proved to be unsuitable for the chosen modeling technique as they were unable to be rated on a scale of **0** to **10** and as the group attempted to determine the standard strengths for these factors, they were all found to be zero and therefore have no impact on the model. That is not to say that these factors do not affect project costs, but they simply did not fit into the context of the proposed model. The original factors were approved by the group with some minor changes to be made in the wording of certain factors.

The next question was for the group to define what LOW, MEDIUM, and HIGH cost overruns and underruns were. Their response is shown in Table 3.1. These ranges were then used later in the interview to determine cost impacts due to combinations of the factors.

The final and most important questions were on determining the standard strengths. Four tables were to be filled out; two representing the standard strengths between the project characteristics and risk events, and two representing the cost impacts from combinations of project characteristics and risk events. In each set, one of the tables represented the worst-case scenario and the other the best-case scenario. For the standard strengths between the project characteristics and risk events, a rating was assigned between **0** and **10**. For the potential cost overruns or underruns caused by the combinations of each project characteristic and risk event, a cost range as defined earlier was predicted. The standard strengths provided by the expert interview are in Appendix F.

4.3.2. Project Manager Interview

The participating project managers were chosen from the mechanical, structural, and electrical groups of the Buildings department within the Company. This department works on industrial projects as well as commercial building projects, but it was specified that the project data gathered was to be from commercial building projects. Seven project managers participated in the survey; two from the initial group chosen were not interviewed due to time constraints and their unavailability.

The project manager interviews were approximately an hour in length and done on an individual basis. The participants were each given a copy of the questionnaire in order to obtain beforehand any documents that would be needed to answer the questions.

Each project manager was asked to select 2 to 3 completed projects that he has worked on within the last few years. Relatively current projects were necessary to ensure that the project manager can still recall the details of the project and accurately answer the questions.

The data from the project manager interview is used to test and validate the model. On each of the projects reviewed during the interviews, the cost overrun or underrun is recorded and the project manager rates the existence of the project characteristics and the occurrence of the risk events listed in the model. Each are rated on a scale of **0** to **10**, with **0** being *poor* and **10** being *excellent*. Appendix G contains the data collected from the interviews that is used to test the model.

4.4 Data Analysis and Results

The project manager interviews produced eighteen projects to use as data for testing the model. Information on the projects was collected as well as the input data necessary for the model. Table 4.1 is a recap of the projects collected and their details such as the project duration, type of project, size of project, and type of owner. Other information was gathered during the interview such as the names of the owner and architect or prime consultant but will not be listed in order to uphold the confidentiality promised to the cooperating design firm.

Table 4.1 Project details

	Type	Size ($)	Design Duration (months)	Const. Duration (months)	Owner Type	Local/ Remote	Discipline
A	Hospital	170,000	21	19	Public	Remote	Electrical
B	Hospital Renovation	160,000	15	19	Public	Local	Electrical
C	Medical/ Dental Bldg	40,000	14	12	Public	Local	Mechanical
D	Hospital	350,000	23	19	Public	Remote	Mechanical
E	Hospital Addition	280,000	18	17	Public	Local	Mechanical
F	Office Bldg Renovation	90,000	N/A	N/A	Private	Local	Mechanical
G	Learning Centre	140,000	6	15	Private	Local	Mechanical
H	Storage Facility	5,500	4	6	Private	Local	Mechanical
I	Storage Facility	6,000	5	9	Private	Remote	Mechanical
J	City Hall	35,000	9	7	Public	Remote	Structural
K	Living Complex	195,00	7	12	Private	Remote	Structural
L	Hospital	165,000	21	19	Public	Remote	Structural
M	LRT Station	120,000	N/A	N/A	Public	Local	Structural
N	Institution Addition	45,000	4	4	Public	Local	Mechanical
O	Hospital Inspections	70,000	N/A	19	Public	Remote	Mechanical
P	Building Evaluation	8,000	4	N/A	Private	Local	Electrical
Q	Generator Construction	50,000	6	2	Private	Local	Electrical
R	Fire Alarm System	55,000	2	3	Private	Remote	Electrical

One of the main problems that was initially to be addressed in this research is the problem of scope creep. For each of the interviews, the interviewees were asked what they feel are the main contributors to scope creep, both internally and externally. The following comments and examples were given on causes of scope creep and cost overruns in general:

- Misunderstandings between the owner and the consultant regarding the services to be provided in the contract.
- Poor communication amongst the design team.
- Poor scope definition at the initial proposal stage.
- Tight timeline with too much work to do.
- Construction site not ready on time; late deliveries of supplies to site.
- Too many people working on the project.
- Lack of design meetings or ineffective design meetings. It is important to have design meetings without the owner in attendance to coordinate and discuss design issues that may be of little interest to the owner.
- Poor coordination from the architect. This can be a result of the architect or others being based out of another city.
- Architectural changes to improve the design that affect all other disciplines and are not compensated for.
- Providing remedial solutions to contractor mistakes.
- Meeting ongoing changes from the owner's group.
- A formal Request For Information (RFI) process initiated by the construction contractor during the construction phase was a bit 'overzealous' and caused extra paperwork and hassle.
- The architect refused to accept responsibility for extra work caused by his failure to properly think through the design before instructing the consultants to proceed.
- Staff members with a lack of work will stretch a project to fill more hours than necessary, thereby billing more to the job. This should be caught by the project

manager, or the project manager should instruct approximately how long each task should take.

- Work may be estimated with the assumption that a junior employee will perform the bulk of the work, but instead the work gets assigned to a senior employee billing at a higher rate.

Project Characteristic Rating Results

The project characteristics that received the lowest ratings during the project manager interviews are the most frequently occurring adverse project characteristics. Likewise the project characteristics with the highest ratings are the least common to cause problems on design projects. The lowest rating project characteristics are *time taken by the owner/prime consultant/architect/engineer to make decisions* and *timeline for design and construction too short*, each receiving an average rating of 4.7. The next lowest rating was given to *willingness of the architect/prime consultant to approach the owner for extra fees* and *project complexity*. The project characteristic that causes the least amount of problems and received the highest rating is the *experience of the consultant's project manager*, with an average score of 7.3. Table 4.2 gives the average rating of each project characteristic in order from the worst-rated to the best-rated characteristic. The complete list of ratings can be seen in Appendix G.

Table 4.2 Average ratings of the project characteristics

Project Characteristics		Average Rating
2.0	Time taken by the owner/prime consultant/architect/engineer to make decisions	4.7
12.0	Timeline for design and construction too short	4.7
1.0	Willingness of the architect/prime consultant to approach the owner for extra fees.	5.1
11.0	Project Complexity	5.1
9.0	Skill set of architect/engineer's design teams.	5.6
4.0	Level of project scope definition between the consultant and owner/prime consultant at the proposal stage	6.0
13.0	Project location	6.0
3.0	Knowledge base of the owner	6.1
7.0	Experience of prime consultant's project lead	6.3
10.0	Experience of the project team with similar projects	6.4
8.0	Skill set of the consultant's design team	6.7
5.0	Definition of scope duties passed on by the consultant's project manager to the design team.	6.8
6.0	Experience of the consultant's project manager	7.3

Figure 4.1 shows the frequency of project characteristic ratings categorized as POOR (**0** to **3**), AVERAGE (**4** to **6**) and EXCELLENT (**7** to **10**). From the histogram, we can see that the *time taken by the owner/prime consultant/architect/engineer to make decisions* was rated POOR the most often followed by the *willingness of the architect/prime consultant to approach the owner for extra fees*. This shows that these project characteristics most frequently cause problems on design projects. *Project location* and *project complexity* were also given the lowest ratings, but these should be interpreted separately as they are factors that are beyond the control of the consultant and only indicative of the types of projects that were chosen for the data collection questionnaire. A POOR rating signifies that the factor caused problems on the project, an AVERAGE rating signifies that the factor performed as expected, and an EXCELLENT rating signifies that the factor did not cause problems on the project.

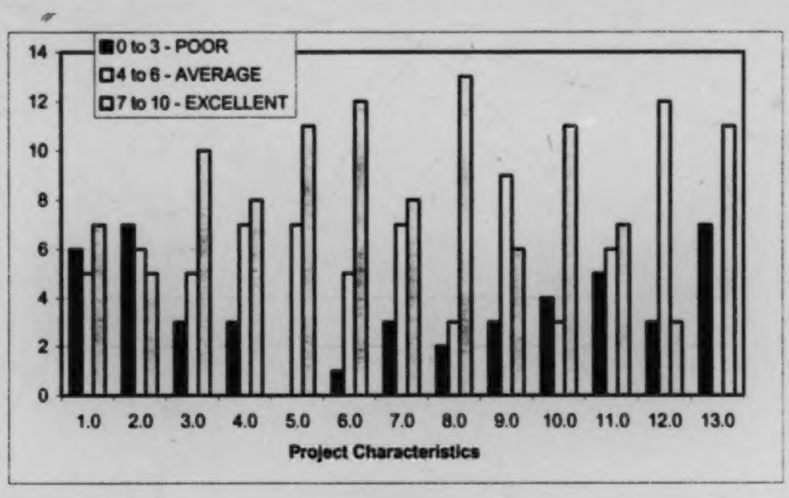


Figure 4.1 Frequency of Project Characteristic Ratings

Risk Event Rating Results

The risk event that received the lowest rating, or is most frequently a problem, is a *poor general contractor and subcontractors*, with an average rating of 4.7. Following close behind are the problems of *over-engineering* and *scope/design changes by the owner, consultants or architect*. *Accuracy of the site investigation* has the best overall score, or is least likely to be a problem, but still with a low average of only 6.2. Table 4.3 lists the risk events in order from the lowest to the highest average rating.

Table 4.3 Average ratings of the risk events

Risk Events		Average Rating
VIII.	General contractor and subcontractors	4.7
V.	Over-engineering	4.8
III.	Scope/design changes by the owner, consultants, or architect	4.9
VI.	Constructability issues	5.2
IV.	Communication amongst the project team	5.3
II.	Design errors or omissions	5.7
VII.	Inadequate design team resources	5.8
I.	Accuracy of site investigation	6.2

Figure 4.2 shows the frequency of risk event ratings categorized as POOR(0 to 3), AVERAGE (4 to 6) and EXCELLENT (7 to 10). *Poor communication amongst the project team* is the most common problem on design projects, and the second most common problems are a *poor general contractor and subcontractors* and *scope/design changes by the owner, consultants, or architect*. *Inadequate design team resources* was rarely a cause of problems for the Company. A complete list of these ratings is in Appendix G.

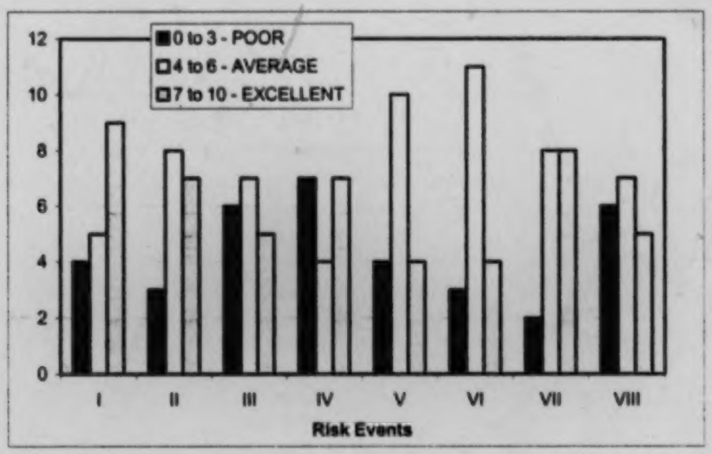


Figure 4.2 Frequency of Risk Event Ratings

Indications from the Standard Strengths

The standard strengths given by the experts give indications as to the factors that have the greatest cost impacts on design projects when coupled with other factors. Project costs are most sensitive to variations in project characteristics when they occur in combination with the risk event of a *poor general contractor and subcontractors*. The next highest rating risk events are *design/scope changes by the owner, consultants or architect* and *communication amongst the project team*. The *experience level of the* *consultant's project manager* is rated as the project characteristic with the highest potential cost impact when coupled with adverse risk events, followed by the *skill set of the consultant's design team* and the *definition of scope duties passed on by the consultant's project manager to the design team.*

The risk event that has the potential to cause the highest cost overruns when combined with adverse project characteristics is *design/scope changes by the owner, consultants or architect*, followed by *inadequate design team resources*, *poor communication amongst the project team*, and a *poor general contractor and subcontractors.* The project characteristics that have the potential to cause the highest cost overruns when combined with adverse risk events are *the experience of the project team with similar projects*, *the level of project scope definition between the consultant and owner/prime consultant at the proposal stage*, and *the experience of the consultant's project manager.*

4.5 Conclusion

This chapter reviewed the development of the interview questionnaires and the interview methodology used for the data collection process. The data collected in the expert interview is used as part of the calculation within the model, and the data collected from the project manager interviews will be used in the next chapter to test and validate the model.

The project characteristics that were identified as having the greatest potential to affect project performance are the *experience level of the consultant's project manager*, *the skill set of the consultant's design team*, *the experience of the project team with* *similar projects*, and *the level of project scope definition between the consultant and owner/prime consultant at the proposal stage*. The most frequently occurring adverse project characteristics are the *time taken by the owner/prime consultant/architect/ engineer to make decisions*, the *timeline for design and construction too short* and *the willingness of the architect/prime consultant to approach the owner for extra fees*.

The risk events that were identified as having the greatest impact on project costs are a *poor general contractor and subcontractors*, *design/scope changes by the owner, consultants or architect* and *poor communication amongst the project team*. The most commonly occurring adverse risk events are *poor communication amongst the project team*, a *poor general contractor and subcontractors*, and *scope/design changes by the owner, consultants, or architect*.

The next chapter explains how the data collected from the project manager interviews was used to validate the model, and the accuracy of the model's predictions based on validation.

5. Model Testing and Validation

5.1 Introduction

The purpose of this chapter is to test and validate the fuzzy logic model for predicting design cost overruns. In order to test the model, the calculations for the model were programmed in Visual Basic 6.0 with a user interface for inputting the data. The model was tested using the project data collected from the project manager interviews as discussed in Chapter 4. Calibrations will be made to the model to improve its accuracy, and then the model was retested with the collected data. The accuracy of the calibrated model is presented and discussed, as well as the sources of error from the collected data.

5.2 Programming of the Model

The programming of the model was done using Visual Basic 6.0. The program uses simple For and If-Then loops combined with simple mathematics to perform the matrix and other calculations in the model. Many different versions of the model were programmed in order to test and compare the use of different composition operations and defuzzification methods as discussed in Chapters 2 and 3. Appendix H provides a sample programming code for a model programmed using the cumulative-minimum composition operation and the centre-of-area method of defuzzification.

The data is input into the model from a form developed within VB 6.0. Once the ratings for each of the project characteristics and risk events are entered, the user clicks on a 'Calculate' button. This button calls up a results form giving the predicted cost overrun or underrun calculated by the model. Figure 5.1 is a screenshot of the input form and Figure 5.2 a screenshot of the results form.

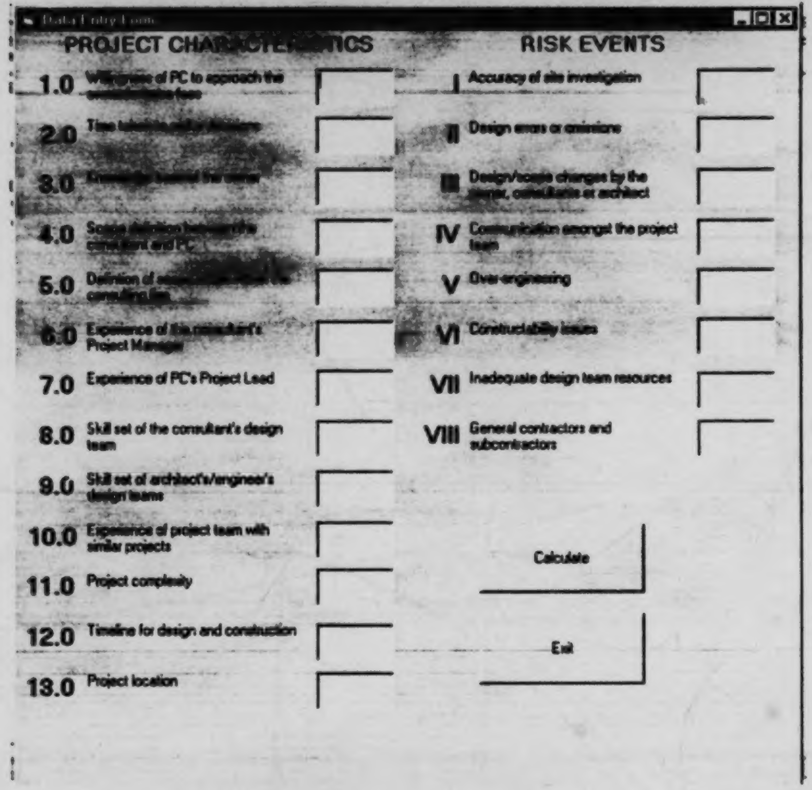
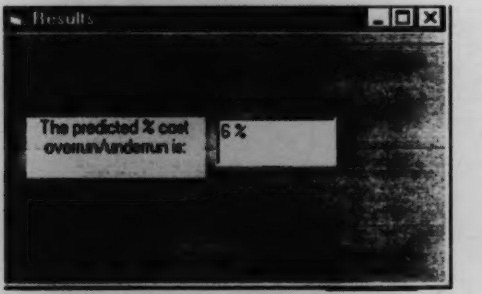

Data Entry Form
PROJECT CHARACTERISTICS
1.0 Willingness of PC to approach the [illegible]
2.0 Time taken [illegible]
3.0 [illegible] the owner
4.0 Scope definition between the consultant and PC
5.0 Definition of [illegible] consulting fee
6.0 Experience of the consultant's Project Manager
7.0 Experience of PC's Project Lead
8.0 Skill set of the consultant's design team
9.0 Skill set of architect's/engineer's design teams
10.0 Experience of project team with similar projects
11.0 Project complexity
12.0 Timeline for design and construction
13.0 Project location
RISK EVENTS
I Accuracy of site investigation
II Design errors or omissions
III Design/scope changes by the owner, consultants or architect
IV Communication amongst the project team
V Over-engineering
VI Constructability issues
VII Inadequate design team resources
VIII General contractors and subcontractors
Calculate
Exit

Figure 5.1 Screenshot of the input form



The predicted % cost overrun/underrun is: 6 %

Figure 5.2 Screenshot of the results form

5.3 Model Validation

The testing data set was collected from project manager interviews as discussed in Chapter 4. It consists of 18 case studies of actual, completed design projects from a design engineering consultant. Details of the case studies used are available in Table 4.1. The testing data set was run through several versions of the model. The purpose of this was to test the suitability of different composition operations and defuzzification methods to find which gave the best results. The composition operations tested are:

- maximum-minimum (max-min), and
- cumulative-minimum (cum-min).

The defuzzification methods tested are:

- centre of area (COA),
- middle of maximum (MOM),
- largest of maximum (LOM), and
- smallest of maximum (SOM).

Based on the output of the model, the mean of maximum defuzzification method gives the same results as the middle of maximum.

The output of the model, as discussed in Chapter 3, is a percent cost overrun or underrun above or below the contract fee. The predicted output will be tested by comparing it to the actual percent cost overrun or underrun on the project. The actual cost overrun/underrun is calculated by subtracting the final project fee, or billed amount, from the actual project cost to the consultant, and dividing by the billed amount (see equation (5-1)). The actual cost to the consultant includes salary costs, company overheads, profit, and other costs incurred on the job.

$$\text{Cost overrun/underrun (\%)} = \frac{\text{Actual Cost (\$)} - \text{Billed Amount (\$)}}{\text{Billed Amount (\$)}} \times 100\% \qquad (5\text{-}1)$$

The accuracy of the model was assessed based on two criteria:

1. The percent difference of the predicted cost overrun/underrun compared to the actual cost overrun/underrun;
2. The accuracy of the associated linguistic variable of the predicted cost overrun/underrun compared to the associated linguistic variable of the actual cost overrun/underrun.

The first testing criterion of comparing the actual and predicted cost overruns/underruns is simply a subtraction of the predicted value minus the actual value to give the positive or negative difference, as shown in equation (5-2).

$$\%\ \text{Difference} = C_{Predicted} - C_{Actual} \tag{5-2}$$

A percent difference of 10% above or below the actual value is deemed acceptable. This is an acceptable margin of error considering the high tolerance for variations in cost overruns and underruns, and the inaccuracy and subjectiveness in estimating the contract fee.

The second criterion involves comparing the linguistic variables of the actual and predicted cost overruns/underruns. In the design context, linguistic terms are often used rather than crisp numbers to describe design cost performance since there tends to be wide margins of variation and therefore tolerance. The use of fuzzy logic in predicting cost overruns and underruns makes linguistic term prediction possible. The ranges associated with the linguistic variables of HIGH, MEDIUM, LOW, etc. are in Table 3.1. There are nine possible ranges, numbered from 0 to 8 that the cost overruns/underruns can fit into, ranging from VERY HIGH for underruns to VERY HIGH for overruns. The predicted and actual values can each be placed into a range. The accuracy is evaluated by determining how many ranges off the predicted value is from the actual value. Predictions within the same range as the actual value (i.e. with a range difference of 0) are deemed acceptable.

In the case where the predicted value falls on the limit of two ranges, the range that is closest to the range of the actual value is chosen. For example, if the predicted output is 10%, this can belong to either the *5% to 10%* (MEDIUM) range or the *10% to 20%* (HIGH) range. If the actual value is 12%, it falls in the HIGH range, and therefore the predicted output is classified in the HIGH range as well.

Table 5.1 gives a summary of the testing results for each of the combinations of composition operations and methods of defuzzification. The table gives the average percent difference of the absolute value between the actual and predicted result, and accuracy of the linguistic predictions displayed as the number of projects with a range difference of 0, 1 and 2 or more (with 18 projects in total). Appendix I contains full tables of the actual and predicted results.

Table 5.1 Results of model testing

Composition Operation	Defuzzification Method	Average % Difference (abs value)	Range Difference = 0	Range Difference = +/- 1	Range Difference = +/- 2^+
Cum-min	COA	26	2	7	9
Max-min	COA	27	3	7	8
Cum-min	MOM	26	3	2	13
Max-min	MOM	26	3	2	13
Cum-min	LOM	26	5	6	7
Max-min	LOM	26	5	5	8
Cum-min	SOM	26	4	2	12
Max-min	SOM	26	4	2	12

As shown in Table 5.1, the results from the testing are unsatisfactory as they do not meet the evaluation criteria. The average percent difference for all methods tested is greater than 10% and is therefore unacceptable, and the linguistic ranges are rarely matched, therefore also unacceptable.

An analysis of the results of the testing shows that the model performed very poorly in estimating cost underruns. Table 5.2 shows that the accuracy of the linguistic ranges for the cost underruns was almost always out by at least 2 ranges. Although seven of the eighteen projects had actual underruns, the model only predicted an underrun in one case. An examination of the standard strengths in the best-case model reveal that they are all low and are therefore not exerting enough influence on the output.

Table 5.2 Results of model testing with overruns and underruns separated

Composition Operation	Defuzzification Method	Average % Difference (abs value)	Range Difference = 0	Range Difference = +/- 1	Range Difference = +/- 2⁺
COST OVERRUNS					
Cum-min	COA	26	2	7	2
Max-min	COA	26	3	7	1
Cum-min	MOM	27	3	2	6
Max-min	MOM	27	3	2	6
Cum-min	LOM	26	5	6	0
Max-min	LOM	26	5	5	1
Cum-min	SOM	29	3	2	6
Max-min	SOM	29	3	2	6
COST UNDERRUNS					
Cum-min	COA	27	0	0	7
Max-min	COA	28	0	0	7
Cum-min	MOM	24	0	0	7
Max-min	MOM	24	0	0	7
Cum-min	LOM	26	0	0	7
Max-min	LOM	26	0	0	7
Cum-min	SOM	22	1	0	6
Max-min	SOM	22	1	0	6

Another observation of the results is that the model is often under-predicting. Many of the actual cost overruns and underruns are above +/- 20%, some even above +/- 50%. This does not coincide with the cost ranges determined by the experts, who claimed that overruns above 20% were very high, and also very uncommon. A check of the standard strengths for the model reveals that rarely was the highest cost range (or lowest for the underrun case) identified as the most likely cost overrun. Only 4 of a possible 104 standard strengths point to a cost overrun of over 20%, and none of the standard strengths point to a cost underrun of less than -20%.

These two observations of the model and the data are dealt with in the next section on calibrating the model to provide more accurate results.

5.4 Model Calibration

Two problems with the initial model were identified in the last section: the model is poorly predicting cost underruns; and the model is under-predicting in certain cases. The model is poorly predicting cost underruns because the standard strengths between the project characteristics and the risk events for the best-case model are too weak. The experts reasoned that most fee estimates are prepared assuming minimal problems on the project, which in turn assumes a best-case scenario for the project. The standard strengths for the best-case scenario were therefore quite low; all except two of them are below **5**, limiting the influence of the underruns on the project output. The first proposed calibration to the model is to normalize the standard strengths of the best-case model. Two of the existing standard strengths are **8** which will become **10**, and the remaining strengths at **5** and below will be doubled. This should improve the influence of the best-case model and enable the model to predict cost underruns, but without changing the relationships between the factors for the best-case model.

The next problem with the original model is that it is under-predicting certain overruns and underruns. It was observed that the majority of the projects with the high cost overruns and underruns are smaller projects. This is logical since the percent overrun/underrun is relative to the size of the project. For example, on a small project of $10,000, if the project is $2,000 over budget this represents a 20% cost overrun. However on a larger project of $100,000, this would only be a 2% overrun, which is considered quite low. Therefore it is necessary to separate the large and the small projects and adjust the ranges used on the small projects. This will address the issue of under-predicting in the majority of cases.

Upon examination of the project sizes and the associated cost overruns and underruns, $55,000 was chosen as the cut-off between large and small projects. This puts 8 projects into the small project category (S1 to S8), and 10 projects into the large project category (L1 to L8). The projects were split into large and small categories and renumbered as per Table 5.3.

Table 5.3 Reclassification of projects

Old Project #	New Project #	Old Project #	New Project #
A	L1	C	S1
B	L2	H	S2
D	L3	I	S3
E	L4	J	S4
F	L5	N	S5
G	L6	P	S6
K	L7	Q	S7
L	L8	R	S8
M	L9		
O	L10		

The cost ranges for the small projects must be amended to attempt to more accurately predict their cost overruns and underruns. The new ranges chosen, based on the given data, are shown in Table 5.4. These values were chosen to best fit the existing data and not chosen by experts as with the previous cost ranges.

Table 5.4 Modified ranges of cost overruns and underruns for small projects

	Cost Range	Linguistic Descriptor
C_0	-100% to -80%	VERY HIGH
C_1	-80% to -50%	HIGH
C_2	-50% to -20%	MEDIUM
C_3	-20% to 0%	LOW
C_4	0%	ZERO
C_5	0% to 20%	LOW
C_6	20% to 50%	MEDIUM
C_7	50% to 80%	HIGH
C_8	80% to 100%	VERY HIGH

After incorporating the above changes the model was retested. The same criteria as before were used with one exception: on large projects a percent difference of 10% between actual and predicted is considered acceptable and on small projects a percent difference of 20% is considered acceptable to account for the increased values of the cost ranges.

5.5 Retesting and Discussion of Results

Table 5.5 gives the testing results for the modified model, as per Table 5.1, and separates the results of the large projects from the small projects. All combinations of the composition operations and defuzzification methods were retested. The same evaluation criteria as before is used for both the large and small projects, with the exception of an allowable percent difference of 20% for small projects. Appendix I contains full tables of the actual and predicted results.

The calibrations to the model proved very successful overall in accurately predicting design cost overruns and underruns. All methods provided results that are within acceptable limits for the average percent difference between the actual values and predicted outputs. The number of linguistic matches have also greatly improved from the original model, especially on the smaller projects. The model is also predicting cost underruns where it previously did not.

Table 5.5 Results of model retesting

Composition Operation	Defuzzification Method	Average % Difference (abs value)	Range Difference = 0	Range Difference = +/- 1	Range Difference = +/- 2$^+$
LARGE PROJECTS					
Cum-min	COA	10	2	2	6
Max-min	COA	10	2	2	6
Cum-min	MOM	8	3	3	4
Max-min	MOM	10	2	3	5
Cum-min	LOM	9	5	2	3
Max-min	LOM	10	4	2	4
Cum-min	SOM	8	5	3	2
Max-min	SOM	9	4	2	4
SMALL PROJECTS					
Cum-min	COA	14	3	1	4
Max-min	COA	15	2	2	4
Cum-min	MOM	9	4	3	1
Max-min	MOM	10	3	4	1
Cum-min	LOM	9	7	1	0
Max-min	LOM	8	7	1	0
Cum-min	SOM	13	4	4	0
Max-min	SOM	13	4	4	0

The model that is most successful in predicting design cost overruns and underruns on both the large and small projects uses the cum-min composition operation and the LOM defuzzification method (shown shaded in Table 5.5). For the large projects, the average percent difference is 9%, and for small projects the average percent difference is also 9%, both within the acceptable limits. The number of linguistic matches on the small projects was excellent with 7 out of 8 project overruns/underruns accurately predicted. The linguistic matches for larger projects are not as successful with 5 out of 10 accurate predictions. However, one of these projects is an outlier whose performance can not be predicted by the model and justification exists to eliminate it from the data set.

This project that shows an abnormality in its data is project L1 (or project A). Project L1 had a large underrun of -38% but the model is predicting an overrun of 10%. The ratings given to the project characteristics were for the most part EXCELLENT, with a few AVERAGE ratings and one POOR rating. The ratings for the risk events, however were AVERAGE to POOR, and therefore the model is predicting a cost overrun. This project shows a profit for the consultant despite its problems because the owner was willing to pay extra money to redesign the project. The original design was in progress when the work was halted temporarily; the original design was then discarded and a new design begun. The consultants, however, were fully compensated for the initial work they had done, thereby paying enough extra to allow them to profit on the job. The model is incapable of taking this scenario into account and therefore the model provides an inaccurate prediction of the cost underrun.

Removing this project from the data set improves the overall accuracy of the model. For the cum-min/LOM version of the model, with the removal of this project the accuracy of the model on large projects has improved to a 6% average difference, with 5 of the 9 predictions giving the correct linguistic range (see Table 5.6).

Table 5.6 Testing results for cum-min/LOM with elimination of outlier project

Composition Operation	Defuzzification Method	Average % Difference (abs value)	Range Difference = 0	Range Difference = +/- 1	Range Difference = +/- 2
LARGE PROJECTS					
Cum-min	LOM	6	5	2	2
SMALL PROJECTS					
Cum-min	LOM	9	7	1	0

5.6 Sources of Error in the Data

The data from the project managers and the experts used in the model for testing and for calculations contains inaccuracies. Multiple project managers completed the project manager questionnaire by subjectively rating factors on their projects and recording the actual cost overruns and underruns. A lack of consistency in the subjective ratings will cause a non-uniform rating scale. This is evident because some of the project managers were noticeably more generous or harsher with the ratings they gave. This will cause inconsistencies in the data used to test the model, and a lack of uniformity between the rated factors and the actual cost overrun or underrun, thereby decreasing the accuracy of the model predictions.

Another potential source of error comes from the source of the data. The data is not based on written records but instead on the memories of the project managers. Recent projects were requested in order to limit this cause of error, but due to the length of the design and construction phases of some projects, the start of the project may date back over three years. This may lead to guessing or speculation by the project manager instead of basing the ratings on actual fact.

Some of the projects selected by the project managers may not have been ideal projects for testing the model. They were asked to select standard projects (i.e. ones that did not have atypical problems that the model could not account for) with both cost overruns and underruns. However, some of the projects selected had enormous cost overruns and underruns. One would hope that overruns of over 75% are not common and some unusual occurrence must have caused this.

Another inaccuracy with the predictions of the model lies in the validity of the actual percent overrun or underrun on a project. Estimating in the design phase is not as rigorous or precise a task as with the construction phase. If the estimated fee is inaccurate or imprecise, then this could be the predominant cause of cost overruns or underruns, more so than any problems that occurred on the project. Therefore when comparing the actual overrun/underrun to the predicted result from the model, it will only be as accurate as the original estimate which determines the contract fee.

There were also inconsistencies in the data provided by the experts. Again, the ratings were subjective, albeit this time the ratings were established by a group. Theoretically, the ratings and predicted cost overruns/underruns given by the experts made sense, but the data obtained during the project manager interviews did not support the experts' ratings. The calibrations that were necessary on the standard strengths of the best-case model are evidence of this.

5.7 Conclusion

This chapter introduced the programming and testing of the model. The performance of the original model was poor due to the fact that the model was not predicting cost underruns and the model was under-predicting many of the values. Calibrations to the model were made in order to correct these problems and predict more accurate results based on the testing data received from project managers. The model was then validated and found to be successful in its prediction of cost overruns and underruns. Sources of error in the data were presented for future considerations when further developing the model.

The limitations of the proposed model and recommendations for its future development are discussed in the next chapter.

6. Conclusion

6.1 Conclusions and Contributions

This thesis presents a model that uses fuzzy logic techniques to predict cost overruns or underruns on commercial building design projects, given the characteristics of the project and the likelihood and severity of risk events. The framework of the model was developed with the aid of a local engineering design firm participating in the research. The standard strengths used in the model and the data for testing the model were gathered through interviews with project managers within the design firm. The model was programmed into Visual Basic 6.0 for testing, calibration, and validation.

This model is a new contribution to the design industry. Previous research exists on the factors causing design cost overruns and their impact. Some of the factors have even been modeled for project managers to test different scenarios to help them with the decision making process. There are no previous studies, however, on the combined effects of project characteristics and risk events on design costs to predict an overall cost overrun/underrun to the project.

The model presented uses binary relations, a fuzzy logic technique, to relate two sets of input factors to predict a third output factor. Fuzzy logic and fuzzy expert systems are modeling tools that are being used more and more in the construction industry. These techniques are being used to model problems in construction to help decision makers choose the most beneficial scenarios for their work, identify problems, select corrective actions for the problems, and many other applications. The amount of research that has used these techniques in the recent past is an indication of their usefulness and applicability to the construction industry. This research has illustrated the usefulness of fuzzy logic in modeling a complex problem that relies heavily on experienced yet subjective judgment.

One of the aims of this research was to define and discuss the problem of scope creep and poor scope definition on design projects. A checklist of items that require suitable definition at the onset of design in order to achieve proper scope definition was developed (see Appendix A). This checklist was modified from a study done by the CII that developed a Project Definition Rating Index (PDRI) for both industrial and building projects (Dumont, 1997; CII, 1999). The checklist is specifically tailored to suit the project duties for a local design engineering firm that provided the data for this research. Refinements were also made to the APEGGA project complexity ratings (APEGGA & AAA, 1998) to better reflect technological complexity in modern buildings (see Appendix B).

The project characteristics and risk events that contribute to cost overruns were identified for use in the model. Although there exist many potential problem sources on design projects, the aim was to identify those that are most significant in their impact on project costs. An analysis of the data collected for use in the model identified the project characteristics and risk events that occur most frequently on projects and have the greatest cost impacts. The project characteristics that were rated as having the greatest potential to affect project costs are:

- The experience level of the consultant's project manager;
- The skill set of the consultant's design team;
- The experience of the project team with similar projects; and

- The level of project scope definition between the consultant and owner/prime consultant at the proposal stage.

The most frequently occurring adverse project characteristics from the data collected were:

- The time taken by the owner/architect/prime consultant/engineer to make decisions;
- A too short timeline for design and construction; and
- An unwillingness of the architect/prime consultant to approach the owner for extra fees.

The risk events that were identified as having the greatest impacts on costs are:

- A poor general contractor and subcontractors;
- Design/scope changes by the owner, consultants or architect; and
- Poor communication amongst the project team.

The most commonly occurring adverse risk events were:

- Poor communication amongst the project team;
- A poor general contractor and subcontractor; and
- Scope/design changes by the owner, consultants or architect.

The model proved to successfully predict cost overruns and underruns on design projects. The model predicted cost overruns and underruns within a 6% average difference on large projects and a 9% average difference on small projects (i.e. less than $55,000). It provided accurate linguistic predictions 7 out of 8 times for small projects and 5 out of 9 times for large projects.

The use of fuzzy logic in the model makes it more realistic in the design context. It enables assessments of the project characteristics and risk events to be made subjectively, which is usually the case in practice. The output of the model is presented both numerically and linguistically, providing the decision maker with a useful and realistic guide to the likely cost overrun or underrun for the project. This feedback is useful to the user in setting an appropriate fee for the project based on its likely performance. The user may also choose to modify those conditions surrounding the project that he or she can control, to change the likely outcome of the project. The modifications to the ratings of the project characteristics and/or risk events can be run through the model to assess their impact on the project cost. The model is therefore useful in assessing the impact on cost of a change in any project condition. This information would be useful in negotiating or re-negotiating the project fee with the owner. This research therefore makes a significant contribution in developing a systematic method of assessing an appropriate design fee and identifying project risks.

6.2 Limitations of the Model and Recommendations for Future Development

This research was a first attempt at modeling design cost overruns. There are, therefore, some limitations to the model and areas for improvement. One of the main limitations is the number of factors chosen for use in the model. Thirteen project characteristics and eight risk events were chosen, because they were deemed the most commonly occurring factors and the factors having the greatest impacts on project costs. There are, of course, many other factors that can affect design projects, albeit smaller, less significant ones, but they will still have impacts on project costs. A more comprehensive list of factors to use in the model would provide a more accurate prediction.

Another limitation of the model is the fact that it does not always take into account bidding conditions. The percent overrun/underrun is relative to the estimated fee, and the estimated fee can vary depending on bidding conditions and other market-driven factors. These factors are not taken into account in the model. On the project manager interview, one of the questions asked for the rate table used to determine the actual costs of the job. In some cases, for those project managers that completed a work-breakdown to determine the project fee and used the rate tables to calculate the hourly labour rate, the profit margin, project complexity, and other bidding conditions will have been taken into account. Typically, though, the rate tables are used solely by the accountants for calculating the actual costs of the job to the company. The project fee may even have been determined based on a higher rate table, but the accountants will use the lowest rate table in order for the job to appear more successful. This also reiterates the problem mentioned in Chapter 5 that the model is only as accurate as the estimated fee.

The data collected for testing the model was somewhat adequate, but slightly limited in that more typical projects are needed to test the model. Ideally, more projects need to be gathered including projects that came in on budget. A future development of this research would be to test the model with ongoing projects to see how well it performs.

The model was developed based on the practices of a single local design engineering firm. Although this firm is a large established firm, it would take further research to determine if the model and its standard strengths are applicable to other firms and members of the construction design industry.

There are several refinements and improvements that could be made to the model to improve its accuracy and usefulness. First of all, the model may be more accurate if it was more tailored to one specific type of project. This model was to be used for commercial building projects, but it could be refined to suit either new buildings or renovations, for example. Furthermore, in this research, small and large projects had to be separated because a single model was not able to predict the percent cost overruns/underruns for all sizes of projects. The size of the projects applicable to the model should be specified, as well as the type of project, and possibly the engineering discipline (e.g. mechanical, electrical, structural, etc.). An alternative to predicting a percent cost overrun/underrun would be to predict an actual dollar value overrun or underrun.

The model would benefit from future research by expanding the model to include more project characteristics and risk events and refining the standard strengths used in the model. A more elaborate survey may provide more accurate standard strengths that are based on real projects instead of theory. There are also other factors that could be taken into account such as the bidding conditions, whether the owner of the project was public or private, and the project delivery method, all of which could be used to classify projects.

A key factor in the accuracy of the model is the contract fee that is used to calculate the actual percent cost overrun/underrun. Further research should examine methods of making the estimates more rigorous and accurate. Another solution would be to include a factor within the model that identifies that amount of time and preparation that was put into the estimate, and the project manager's confidence in his or her estimate, to determine the accuracy of the estimate, or to rate the project manager based on the accuracy of their previous estimates. The estimates from previous jobs could be compared to the actual costs of the jobs to assess the project manager's estimating abilities.

One of the inaccuracies in the data of the model is that the project ratings are not always evaluated on the same scale. Increased uniformity of the project ratings could reduce this inaccuracy. Categories could be developed for each rating of each factor, and the interviewee need only chose the appropriate category that his or her project factors fall. For example, in this research the project complexity rating given by the project manager was based on a table that classified types of buildings into five categories of complexity. The experience of the consultant's project manager and the prime consultant's project lead could be categorized into the number of years of experience in the industry and the number of projects managed. The skill set of the design teams could be categorized by the number of junior and senior designers, the number of years of experience, and a rating of the designer's abilities (e.g. poor, average, and excellent).

The design industry could greatly benefit from future research in the area of controlling and managing project costs. Research on project control has traditionally been more focused on the construction phase of projects rather than the design phase. This research was a first attempt at addressing the effects of combinations of factors on design project costs. The results of this research have helped to identify some of the issues that need to be addressed in conducting future research in this area.

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APPENDIX A
Scope of Work Checklist

Modified from the Project Definition Rating Index (PDRI) for Building Projects *by the Construction Industry Institute, 1999.*

BASIS OF PROJECT DECISION

A. Business Strategy
- A1. Building Use Requirements
- A2. Facility Requirements
- A3. Future Expansion/Alteration

B. Owner Philosophies
- B1. Reliability Philosophy
- B2. Maintenance Philosophy
- B3. Operating Philosophy
- B4. Design Philosophy

C. Project Requirements
- C1. Value-Analysis Process
- C2. Project Design Criteria
- C3. Evaluation of Existing Facilities
- C4. Scope of Work Overview
- C5. Project Schedule
- C6. Project Cost Estimate

BASIS OF DESIGN

D. Site Information
- D1. Site Layout
- D2. Site Surveys
- D3. Civil/Geotechnical Information
- D4. Governing Regulatory Requirements
- D5. Environmental Assessments
- D6. Utility Sources with Supply Conditions
- D7. Site Life Safety Consideration
- D8. Special Water and Waste Treatment

E. Building Programming
- E1. Building Summary Space List
- E2. Circulation and Open Space Requirements
- E3. Loading/Unloading/Storage Facilities
- E4. Room Data Sheets

F. Building/Project Design Parameters
- F1. Civil/Site Design
- F2. Architectural Design
- F3. Structural Design
- F4. Mechanical Design
- F5. Electrical Design
- F6. Building Life Safety Requirements
- F7. Constructability Analysis
- F8. Technological Sophistication

G. Equipment
- G1. Equipment List
- G2. Equipment Location Drawings
- G3. Equipment Utility Requirements

EXECUTION APPROACH

H. Deliverables
- H1. CADD/Model Requirements
- H2. Documentation/Deliverables

I. Project Control
- I1. Project Quality Assurance and Control
- I2. Project Cost Control
- I3. Project Schedule Control Requirements
- I4. Risk Management
- I5. Safety Procedures

J. Project Execution Plan
- J1. Project Organization
- J2. Owner Approval Requirements
- J3. Project Delivery Method
- J4. Design/Construction Plan & Approach
- J5. Substantial Completion Requirements

BASIS OF PROJECT DECISION

A. Business Strategy

A1. Building Use Requirements

- Retail
- Institutional
- Instructional
- Medical
- Research
- Multimedia
- Office
- Light Manufacturing
- Storage
- Food Service
- Recreational

A2. Business Plan

- Funding available
- Cost and financing
- Schedule milestones (including known deadlines)

A3. Facility Requirements

- Number of occupants
- Net and gross square footage by area uses
- Classroom size
- Number of laboratory stations
- Occupant accommodation requirements (i.e., number of hospital beds, number of desks, number of workstations, on-site child care, on-site medical cars, cot space, etc.)
- Volume
- Support infrastructure
- Linear feet of display space

A4. Future Expansion/Alteration

- Provisions for site space of possible future expansion up or out
- Technologically advances facility requirements
- Flexibility or adaptability for future uses
- Future phasing plan

A5. Site Selection Considerations

- General geographic location
    - Available utilities
    - Existing facilities
- Environmental issues
- Weather/climate

B. Owner Philosophies

B1. Reliability Philosophy

- Critical systems redundancy
- Architectural/structural/civil durability
- Mechanical/electrical/plumbing reliability

B2. Maintenance Philosophy

- Daily occupancy loads
- Maximum building occupancy requirements
- Equipment monitoring requirements
- Energy conservation programs
- Selection of materials and finishes
- Requirements for building finishes

B3. Operating Philosophy

- Operating schedule/hours
- Provisions for building rental or occupancy assignments (i.e., by room, floor, suite) including flexibility of partitioning

B4. Design Philosophy

- Design life

C. Project Requirements

C1. Value-Analysis Process (*Extra fee items*)

- Discretionary scope issues
- Expensive materials of construction
- Life-cycle analysis of construction methods and structure

C2. Project Design Criteria

- Level of design detail required
- Climatic data
- Codes and standards
    - National
    - Owner specific
    - Local
    - International
- Sole source requirements for equipment or systems
- Insurance underwriter requirements

C3. Evaluation of Existing Facilities

- Capacity
    - Power
    - Fire water
    - Sanitary sewer
    - Security
    - Utilities (i.e., potable water, gas, oil)
    - Waste treatment/disposal
    - Telecommunications
    - Storm water containment system/filtration
- Access
    - Rail
    - Roads
    - ADA or local standards
- Parking areas
- Type and size of building/structures

C4. Scope of Work Overview

C5. Project Schedule

C6. Project Cost Estimate

- Construction contract estimate
- Professional fees
- Contingencies
- Cost escalation for elements outside the project cost estimate
- Miscellaneous expenses including but not limited to:
    - Specialty consultants
    - Inspection and testing services
    - Bringing utilities to the site
    - Environmental impact mitigation measures
    - Local authority permit fees
    - Occupant moving and staging costs
    - Site surveys, soils tests

BASIS OF DESIGN

D. Site Information

D1. Site Layout

- Access (e.g., road, rail, marine, air)
- Construction access
- Historical/cultural

- Trees and vegetation
- Site massing and context constraints or guidelines (i.e., how a building will look in three dimensions at the site)
- Access transportation parking, delivery/service, and pedestrian circulation considerations
- Open space, street amenities, "urban context concerns"
- Climate, wind, and sun orientation for natural lighting views, heat loss/gain, energy conservation, and aesthetic concerns

D2. Site Surveys

- Legal property descriptions with property lines
- Easements
- Rights-of-way
- Drainage patterns
- Deeds
- Definition of final site elevation
- Benchmark control systems
- Setbacks
- Access and curd cuts
- Proximity to drainage ways and flood plains
- Known below grade structures and utilities (both active and inactive)
- Trees and vegetation
- Existing facility locations and conditions
- Solar/shadows

D3. Civil/Geotechnical Information

- Depth to bedrock
- General site description (e.g., terrain, soils type, existing structures, spoil removal, areas of hazardous waste, etc.)
- Expansive or collapse potential of soils
- Fault line locations
- Spoil area for excess soil (i.e., location of on-site area or off-site instructions)
- Seismic requirements
- Water table elevation
- Flood plain analysis
- Soil percolation rate and conductivity
- Ground water flow rates and directions
- Need for soil treatment or replacement
- Description of foundation design options
- Allowable bearing capacities
- Pier/pile capacities
- Paving design options
- Overall site analysis

D4. Governing Regulatory Requirements

- Construction
- Unique requirements
- Environmental
- Structural calculations
- Building height limits
- Setback requirements
- Fire
- Building
- Occupancy
- Special
- Signage
- Historical issues
- Accessibility
- Demolition
- Solar
- Platting
- Air/water
- Transportation

D5. Environmental Assessments

- Archeological
- Location in an EPA air quality non-compliance zone
- Location in a wet lands area
- Environmental permits now in force
- Existing contamination
- Location of nearest residential area
- Ground water monitoring in place
- Downstream uses of ground water
- Existing environmental problems with the site
- Past/present use of site
- Noise/vibration requirements
- Air/water discharge requirements and options evaluated
- Discharge limits of sanitary and storm sewers identified
- Detention requirements
- Endangered species
- Erosion/sediment control

D6. Utility Sources with Supply Conditions

- Potable water
- Drinking water
- Cooling water
- Fire water
- Sewers
- Instrument air
- Facility air
- Heating water
- Gases
- Steam
- Electricity (voltage levels)
- Communications (e.g., data, cable television, telephones
- Special requirement (e.g., deionized water or oxygen)

D7. Site Life Safety Consideration

- Wind direction indicator devices (e.g., wind socks)
- Fire monitors and hydrants
- Flow testing
- Access and evacuation plan
- Available emergency medical facilities
- Security considerations (site illumination, access control)

D8. Special Water and Waste Treatment

- Wastewater treatment
  - Process waste
  - Sanitary waste
- Waste disposal
- Storm water containment and treatment

E. Building Programming

E1. Program Statement

- A performance statement outlining what goals are to be stained (e.g., providing sufficient lighting levels to accomplish the specified task safely and efficiently)
- A measure that must be achieved (e.g., 200 foot-candles at surface of surgical table)
- A test which is an accepted approach to establish that the criterion has been met (e.g., using a standard light meter to do the job)

E2. Building Summary Space List

- Building population
- Special technology considerations

- Administrative offices
- Lounges
- Food service cafeteria
- Conference rooms
- Vending alcoves
- Janitorial closets
- Elevators
- Stairs
- Loading docks
- Dwelling units
- Classrooms
- Laboratories
- Corridors
- Storage facilities
- Mechanical rooms
- Electrical rooms
- Parking space
- Entry lobby
- Restrooms
- Data/computer areas

E3. Circulation and Open Space Requirements

- Exterior
  - Service dock areas and access
  - Circulation to parking areas
  - Passenger drop-off areas
  - Pedestrian walkways
  - Courtyards, plazas, or parks
  - Landscape buffer areas
  - Unbuildable areas (e.g., wetlands or slopes)
  - Sidewalks or other pedestrian routes
  - Bicycle facilities
  - Lobbies and entries
  - Security considerations (e.g., card access or transmitters)
  - Snow removal plan
  - Postal and newspaper delivery
  - Waste removal
  - Fire and life-safety circulation considerations
- Interior
  - Interior aisle ways and corridors
  - Vertical circulation (i.e., personnel and material transport including elevators and escalators)
  - Directional and location signage

E4. Loading/Unloading/Storage Facilities

- Storage facilities to be provided and/or utilized
- Refrigeration requirements and capabilities
- Mail/small package delivery
- Recycling requirements

E5. Transportation Requirements

- Facility access requirements based on transportation
- Drive-in doors
- Extended ramps for low clearance trailers
- Rail car access doors
- Service elevators
- Loading docks
- Temporary parking

E6. Room Data Sheets

- Critical dimensions
- Technical requirements (e.g., fireproof, explosion resistance, X-ray)

- Furnishing requirements
- Equipment requirements
- Audio/visual (A/V) data and communication provisions
- Lighting requirements
- Utility requirements
- Security needs including access/hours of operation
- Finish type
- Environmental issues
- Acoustics/vibration requirements
- Life-safety

E7. Window Treatment Considerations

- Blocking of natural light
- Exterior blinds
- Glare reducing windows
- Interior blinds

F. Building/Project Design Parameters

F1. Civil/Site Design

- Service and storage requirements
- Elevation and profile views
- High point elevations for grade, paving, and foundations
- Location of equipment
- Minimum overhead clearances
- Storm drainage system
- Location and route of underground utilities
- Site utilities
- Earth work
- Subsurface work
- Paving/curbs
- Landscape/xeriscape
- Fencing/site security

F2. Architectural Design

- Determination of metric (hard/soft) versus Imperial units
- Requirements for building location/orientation horizontal and vertical
- Access requirements
- Nature/character of building design (e.g., aesthetics)
- Construction considerations
- American with Disabilities Act requirements or other local access requirements
- Architectural Review Boards
- Planning and zoning review boards
- Circulation considerations
- Seismic design considerations
- Color/material standards
- Hardware standards
- Furniture, furnishings, and accessories criteria
- Design grid
- Floor to floor height

F3. Structural Design

- Structural system (e.g., construction materials, constraints)
- Seismic requirements
- Foundation requirements

- Corrosion control requirements/required protective coatings
- Client specifications (e.g., basis for design loads, vibration, deflection)
- Future expansion/flexibility considerations
- Design loading parameter (e.g., live/dead loads, design loads, collateral load capacity, equipment/material loads, wind/snow loads, uplift)
- Functional spatial constraints

F4. Mechanical Design

- Special ventilation or exhaust requirements
- Equipment/space special requirements with respect to environmental conditions (e.g., air quality, special temperatures)
- Energy conservation and life cycle costs
- Acoustical requirements
- Zoning and controls
- Air circulation requirements
- Outdoor design conditions (e.g., minimum and maximum yearly temperatures)
- Indoor design conditions (e.g., temperature, humidity, pressure, air quality)
- Building emissions control
- Utility support requirements
- System redundancy requirements
- Plumbing requirements
- Special piping requirements
- Seismic requirements

F5. Electrical Design

- Power sources with available voltage and amperage
- Special lighting considerations (e.g., lighting levels, color rendition)
- Voice, data, and video communications requirements
- Uninterruptible power source (UPS) and/or emergency power requirements
- Energy consumption/conservation and life cycle costs
- Ability to use daylight in lighting
- Seismic requirements
- Lightning/grounding requirements

F6. Building Life Safety Requirements

- Fire resistant requirements
- Explosion resistant requirements
- Area of refuge requirements in case of catastrophe
- Safety and alarm requirements
- Fire detection and/or suppression requirements
- Eye wash stations
- Safety showers
- Deluge requirements and foam
- Fume hoods
- Handling of hazardous materials
- Isolation facilities
- Sterile environments
- Emergency equipment access
- Personal shelters
- Egress
- Public address requirements

- Data or communications protection in case of disaster or emergency
- Fall hazard protection
- Gas hazard detection

F7. Constructability Analysis (*Extra fee items*)

- Constructability program in existence
- Construction knowledge/experience used in project planning
- Early construction involvement in contracting strategy development
- Developing a construction-sensitive project schedule
- Considering major construction methods in basic design approaches
- Developing site layouts for efficient construction
- Early identification of project team participants for constructability analysis
- Usage of advanced information technologies

F8. Technological Sophistication

- Video conferencing
- Internet connections
- Advanced audio/visual (A/V) connections
- Personnel sensing
- Computer docking stations
- "Smart" heating or air-conditioning
- Intercommunication systems
- Security systems
- Communication systems
- Conveyance systems

G. Equipment

G1. Equipment List

- Process
- Medical
- Food servicing/vending
- Trash disposal
- Distributed control systems
- Material handling
- Existing sources and characteristics of equipment
    - Relative sizes
    - Location
    - Materials of construction
    - Equipment related access
    - Weights
    - Capacities
    - Insulation and painting requirements
    - Equipment delivery time, if known
    - Vendor, model, and serial number once identified

G2. Equipment Location Drawings

- Plan and elevation views of equipment and platforms
- Location of equipment rooms
- Physical support requirement (e.g., installation bolt patterns)
- Coordinates or location of all major equipment

G3. Equipment Utility Requirements

- Power and/or all utility requirements
- Design temperature and pressure
- Gas
- Flow diagrams
- Diversity of use
- Water

EXECUTION APPROACH

H. Deliverables

H1. CADD/Model Requirements

- Software system required by client (e.g., AutoCAD, Intergraph)

- Will the project be required to be designed using 2D or 3D CADD? Will rendering be required?
- If 3D CADD is to be used, will a walk-through simulation be required?
- Owner/contractor standard symbols and details
- How will data be received and returned to/from the owner?
  - Disk
  - Tape
  - Full-size mock-ups
  - Electronic transfer
  - Reproducibles

H2. Documentation/Deliverables

- Drawings and specifications
- Project correspondence
- Maintenance and operating information/startup procedures (*Extra fee item*)
- Facility keys, keying schedules, and access codes
- Project data books (quantity, format, contents, and completion date)
- Equipment folders (quantity, format, contents, and completion date)
- Design calculations (quantity, format, contents, and completion date)
- Spare parts and maintenance stock (special forms) (*Extra fee item*)
- Record (as-built) documents (*Extra fee item*)
- Quality assurance documents (*Extra fee item*)
- Inspection documents
- Certificates of inspection
- Shop drawings and samples

I. Project Control

I1. Project Quality Assurance and Control

- Responsibility during design and construction
- Submittals and shop drawing approach
- Inspection reporting requirements
- Progress photos
- Reviewing changes and modifications
- Communication documents (e.g., RFIs, RFQs)
- Commissioning tests (*Extra fee item*)

I2. Project Cost Control (*Prime consultant*)

- Financial (client/regulatory)
- Phasing or area sub-accounting
- Capital vs. non-capital expenditures
- Report requirements
- Payment schedules and procedures
- Cash flow projections/draw down analysis
- Cost code scheme/strategy
- Costs for each project phase
- Periodic control check estimates
- Change order management procedure, including scope control

I3. Project Schedule Control Requirements (*Prime consultant*)

- Milestones
- Unusual schedule considerations
- Required submissions and/or approvals
- Required documentation and responsible party
- Baseline vs. progress to date

- Long-lead or critical pacing equipment delivery
- Critical path activities
- Contingency or "float time"
- Permitting or regulatory approvals
- Activation and commissioning
- Liquidated damages/incentives
- Selection, procurement, and installation of equipment
- Design of interior spaces (including furniture and accessory selection)
- Tie-ins, service interruptions, and road closures

I4. Risk Management

- Design risks
  - Expertise
  - Work load
  - Communication
  - Experience
  - Teamwork orientation
  - Integration and coordination
- Construction risks
  - Weather
  - Strikes
  - Scope growth
  - Availability of craft labor and construction materials
  - Differing/unforeseen/difficult site conditions
  - Long-lead item delays
  - Inflation
- Management risks
  - Availability of designers
  - Timely decisions
  - Human error

I5. Safety Procedures (*Owner or Prime Consultant*)

- Hazardous material handling
- Interaction with the public
- Working at elevations/fall hazards
- Evacuation plans and procedures
- Drug testing
- First aid stations
- Accident reporting and investigation
- Pre-task planning
- Safety orientation and planning
- Safety incentives
- Other special or unusual safety issues

J. Project Execution Plan

J1. Project Organization

- Core team members
- Project manager assigned
- Project sponsor assigned
- Working relationships between participants
- Communication channels
- Organizational chart
- Approval responsibilities/responsibility matrix

J2. Owner Approval Requirements

- Milestones for drawing approval by phase
  - Comment
  - Bid Issues (public or private)
  - Approval
  - Construction

- Durations of approval cycle compatible with schedule
- Individual(s) responsible for reconciling comments before return
- Types of drawings/specifications

J3. Project Delivery Method

- Designer and contractor qualification selection process
- Selected methods (e.g., design/build, CM at risk, competitive sealed proposal, bridging, design-bid-build)
- Contracting strategies (e.g., lump sum, cost-plus)
- Design/build scope package considerations

J4. Design/Construction Plan & Approach (*Prime Consultant*)

- Responsibility matrix
- Subcontracting strategy
- Work week plan/schedule
- Organizational structure
- Work Breakdown Structure (WBS)
- Construction sequencing of events
- Site logistics plan
- Safety requirements/program
- Identification of critical activities that have potential impact on facilities (i.e., existing facilities, crane usage, utility shut downs and tie-ins, testing)
- Quality assurance/quality control (QA/QC) plan
- Design and approvals sequencing of events
- Equipment procurement and staging
- Contractor meeting/reporting schedule
- Partnering or strategic alliances
- Alternative dispute resolution
- Furnishings, equipment, and built-ins responsibility

J5. Substantial Completion Requirements

- Have specific requirements for SC responsibilities been developed?
- Have warranty, permitting, insurance, and tax implications been considered?
- Commissioning
    - Occupancy phasing
    - Final code inspection
    - Verification
    - Training
    - Equipment/systems startup and testing
    - Calibration
    - Documentation
    - Acceptance
- Landscape requirements
- Punchlist completion plan and schedule
- Substantial completion certificate

APPENDIX B
Project Complexity Categories

Categories of Buildings

Based on the Recommended Conditions of Engagement and Schedule of Professional Fees for Building Projects, by AAA & APEGGA

Category 1

- Warehouse (10% maximum office area not exceeding 600m^2)
- Barn, Stable, Storage Shed, Kennel
- Demolition (total)
- Apartment, Multiple Residential, Row Housing, Cluster and Townhousing
- Non-complex Motel, Motor Hotel, and Apartment Hotel
- Building shell only for: Summer Camp, Park Building, Resort/Tourist Building

Category 2

- Armed Forces Warehouses, Armory, Drill Hall
- Customs, Immigration Building
- Marina, Trailer Park
- Maintenance Building, Service Garage, Gas Station, Parking Structure (above ground and free standing)
- Commercial Office Building, General Purpose Office Building (tenant layouts not included)
- Mercantile Building – Store, Shop, Market Building, Shopping Centre and Department Store (tenant layouts not included)
- Student or Institutional Residence, Senior Citizens' Apartment
- Industrial Building such as Cold Storage, Printing, Bakery, Laundry or Light Manufacturing Facility
- Kindergarten and Elementary School
- Community Centre (single hall with support space)

Category 3

- Junior and Senior Academic High School, University and College Non-Technical Classroom Building
- Administrative Office Building, Owner Occupied Office Building (provided tenant work is tendered with the building shell)
- Grandstand, Stadium, covered Ice Rink with minimal support facility
- Summer Camp, Park Building, Resort/Tourist Building
- Facility for a high level of residential support including Specialized Housing, Senior Citizens' Lodge
- Animal Clinic
- Store, Market Building, Warehouse Sales Outlet
- Hotel or Complex Motor Hotel
- Club: Town, Country, Sports, Health
- Settlement House, Inner City Core Housing, "Y" Facility

Category 4

- Amusement Park Building
- Community Multi-Use Centre

- Swimming Pool, Ice Arena, Recreation Building, Physical Education Building
- Zoo, Animal Hospital, Botanical Garden
- Licensed Day Care
- University, College Non-Technical Classroom Building and Vocational Senior High School
- Theatre, Opera House, Auditorium, Concert Hall
- Cemetery Chapel, Mausoleum, Crematorium
- Funeral Home, Undertaking Establishment
- Museum (exhibition hall as shell space, non-complex program without specialized environmental conditions)
- Bar, Restaurant, Lounge
- Place of Worship, Monastery, Convent
- Bank and Trust Company Facility
- Stock Exchange
- Convention Hall, Exhibition Building
- Plant: Manufacturing, Processing, Specialized Storage
- Police Station, Fire Station, Emergency Measures Facility, Ambulance Facility
- Parking Structure above ground attached to an existing building or new building

Category 5

- Facility for High Level Medical Care including Active Treatment Hospital, Combined Active Treatment and Auxiliary Hospital with Nursing Home
- Medical Research Building, Medical Clinic, Blood Donor and Transfusion Centre
- Communications Building, Radio or TV Facility, Studio, Computer Centre
- Science Building
- Laboratory Building
- Dental Building
- Observatory, Planetarium
- Museum, Art Gallery
- Aquarium
- Plus 15 or below grade pedway, link between buildings, Rapid Transit Station, Passenger Loading Bridge
- Maximum or Mixed Security Level Institution, Jail, Penitentiary, Reformatory, Corrections Centre, Remand Centre, Rehabilitation Centre
- Telephone Equipment Building
- Minimum Security Level Institution, Jail, Penitentiary, Reformatory, Corrections Centre, Remand Centre, Rehabilitation Centre
- Terminal: Traffic, Passenger, Freight, Road, Rail, Air, Water, Armed Forces Hangar or Terminal or Specialty Building
- City Hall, Town Hall
- Chancery and Embassy, Consulate or Legation in Alberta
- Medium Security Level Institution, Jail, Penitentiary, Reformatory, Corrections Centre, Remand Centre, Rehabilitation Centre
- Facility for a Medium Level of Medical Care including Mental Health Hospital, Auxiliary Hospital, combined Auxiliary Hospital and Nursing Home, Special Care Facility (e.g., for severely handicapped children), Convalescent Rehabilitation Facility
- Parliament Building, Post Office, Mint, Treasury, Courthouse, Archives Building, Library
- Air Traffic Control Tower, Control Centre and Flight Service Station
- Tenant Space Planning

APPENDIX C

List of Project Characteristics and Risk Events

List of Other Project Characteristics

- Does prime consultant pay promptly
- Financial history of owner
- Financial backing for project
- Agreement between the prime consultant and the owner
- Has the architect/prime consultant been worked with on previous projects
- Relationship with architect/prime consultant
- Has the owner been worked for on previous projects
- Relationship with owner
- Relationship of the architect/prime consultant with the owner
- Amount of time allowed to submit the fee proposal letter
- Project Size
- Complexity of site
- Type of design contract
- Have other subconsultants been worked with before
- Relationship with other subconsultants
- Do subconsultants provide material on time

List of Other Risk Events

- Type of construction contract – Lump sum, percentage fee, etc.
- Previous experience with contractor
- Quality of primary vendors/suppliers
- Amount of rework during design
- Productivity of design team
- Changes in materials
- Changes in construction methods
- Coordination of consultants
- Coordination of contractors
- Amount of supervision/site visits required during construction
- Construction productivity – labour shortage, unskilled labourers
- Construction supplies not available/ready on time, causing need for redesign
- Weather

APPENDIX D
Expert Interview

Expert Interview

The following question should be answered based on your general knowledge and experience. If a question can have multiple answers, think of the most common or likely case or scenario as opposed to the rare occurrences.

A. The following project characteristics have been identified as the most significant characteristics likely to contribute to a cost overrun/underrun. Are there any other characteristics that frequently contribute to cost overruns or savings?

1.0 Willingness of the prime consultant to approach the owner for extra fees.

2.0 Time taken by the owner/prime consultant/architect/engineer to make decisions.

3.0 Knowledge base of the owner.

4.0 Level of project scope definition between the consultant and owner/prime consultant at the proposal stage.

5.0 Definition of scope duties passed on by the project manager's project manager to the design team.

6.0 Experience of the consultant's project manager.

7.0 Experience of prime consultant's project lead.

8.0 Skill set of the consultant's design team.

9.0 Skill set of architect/engineer's design teams.

10.0 Experience of the project team with similar projects.

11.0 Project complexity.

12.0 Timeline for design and construction.

13.0 Project location.

Other ____

B. The following risk/opportunity events have been identified as having the most significant impacts on cost. Are there any other risk/opportunity events that frequently lead to cost overruns or savings?

I. Accuracy of site investigation.

II. Design errors or omissions.

III. Scope/design changes by the owner, consultants or architect.

IV. Communication amongst the project team.

V. Over-engineering.

VI. Constructability issues.

VII. Inadequate design team resources.

VIII. General contractor and subcontractors.

Other ______________________________

C. For the project characteristics and risk events in Table 1, give a rating between 0 and 10 that represents the sensitivity of the impact on project cost to variations in the existence of the project characteristic, given that the risk/opportunity event occurs in its worst state. 10 represents high sensitivity, 0 represents low sensitivity.

D. For the project characteristics and risk events in Table 2, give a rating between 0 and 10 that represents the sensitivity of the impact on project cost to variations in the existence of the project characteristic, given that the risk/opportunity event occurs in its best state. 10 represents high sensitivity, 0 represents low sensitivity.

E. For each of the project characteristics and risk events in Table 3, give a percentage, or percentage range, of the cost overrun/underrun that is most likely to result assuming the characteristic exists at its worst state and a worst case scenario of the risk/opportunity event occurs.

F. For each of the project characteristics and risk events in Table 4, give a percentage, or percentage range, cost overrun/underrun that is most likely to result assuming the characteristic exists at its best state and a best case scenario of the risk/opportunity event occurs.

WITH RESPECT TO YOUR BUDGETED FEES ON A PROJECT:

G. What do you consider a HIGH cost overrun?

0% to 2% 2% to 5% 5% to 10% 10% to 20% 20% to 50% 50%+

H. What do you consider a MEDIUM cost overrun?

0% to 2% 2% to 5% 5% to 10% 10% to 20% 20% to 50% 50%+

I. What do you consider a LOW cost overrun?

0% to 2% 2% to 5% 5% to 10% 10% to 20% 20% to 50% 50%+

J. What do you consider a HIGH cost underrun?

-50%+ -50% to -20% -20% to -10% -10% to –5% -5% to -2% -2% to 0%

K. What do you consider a MEDIUM cost underrun?

-50%+ -50% to -20% -20% to -10% -10% to –5% -5% to -2% -2% to 0%

L. What do you consider a LOW cost underrun?

-50%$^+$ -50% to -20% -20% to -10% -10% to –5% -5% to -2% -2% to 0%

M. What are the main causes of "Scope Creep"?

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

Appendix D Expert Interview

Table 1. Standard Strengths between Project Characteristics and Risk/Opportunity Events – Worst Case Scenario

Risk Events / Project Characteristics	I. Poor site investigation	II. Design errors	III. Design/scope Changes	IV. Poor communication	V. Over-engineering	VI. Poor constructability	VII. Inadequate design resources	VIII. Poor general contractor
1.0 Willingness to approach owner								
2.0 Time taken for decisions								
3.0 Knowledge base of owner								
4.0 Level of proj scope definition								
5.0 Definition of designers duties								
6.0 Experience of consultant's PM								
7.0 Experience of architect lead								
8.0 Skill set of consult. designers								
9.0 Skill set of arch designers								
10.0 Experience with similar proj								
11.0 Project complexity								
12.0 Timeline								
13.0 Project location								

Table 2. Standard Strengths between Project Characteristics and Risk/Opportunity Events – Best Case Scenario

Risk Events Project Characteristics	**I.** Good site investigation	**II.** No design errors	**III.** No Design/scope changes	**IV.** Excellent communication	**V.** No over-engineering	**VI.** Excellent constructability	**VII.** Adequate design resources	**VIII.** Excellent general contractor
1.0 Willingness to approach owner								
2.0 Time taken for decisions								
3.0 Knowledge base of owner								
4.0 Level of proj scope definition								
5.0 Definition of designers duties								
6.0 Experience of consultant's PM								
7.0 Experience of architect lead								
8.0 Skill set of consult. designers								
9.0 Skill set of architect designers								
10.0 Experience with similar proj								
11.0 Project complexity								
12.0 Timeline								
13.0 Project location								

Table 3. Cost Overruns/Underruns resulting from Project Characteristics and Risk Events – Worst Case Scenario

Risk Events / **Project Characteristics**	**I.** Poor site investigation	**II.** Design errors	**III.** Design/scope Changes	**IV.** Poor communication	**V.** Over-engineering	**VI.** Poor constructability	**VII.** Inadequate design resources	**VIII.** Poor general contractor
1.0 Unwilling to approach owner								
2.0 Time taken for decisions slow								
3.0 Knowledge base of owner low								
4.0 Level of proj scope def'n low								
5.0 Poor def'n of designers duties								
6.0 Experience of consult. PM low								
7.0 Experience of architect lead low								
8.0 Low skill of consult. designers								
9.0 Low skill of architect designers								
10.0 No exp. with similar projects								
11.0 High project complexity								
12.0 Short Timeline								
13.0 Project location remote								

Table 4. Cost Overruns/Underruns resulting from Project Characteristics and Opportunity Events – Best Case Scenario

Risk Events Project Characteristics	I. Good site investigation	II. No design errors	III. No Design/scope changes	IV. Excellent communica-tion	V. No over-engineering	VI. Excellent constructa-bility	VII. Adequate design resources	VIII. Excellent general contractor
1.0 Willing to approach owner								
2.0 Time taken for decisions fast								
3.0 Knowled. base of owner high								
4.0 Level of proj scope def'n high								
5.0 High def'n of designers duties								
6.0 Experience of consult. PM high								
7.0 Experience of architect lead high								
8.0 High skill of consult. designers								
9.0 High skill of architect designers								
10.0 Exp. with similar proj high								
11.0 Project complexity simple								
12.0 Adequate Timeline								
13.0 Project location local								

Definition of Terms

The **Architect** is often the **Prime Consultant** to the owner, but not in every case. The terms are used separately but if the Architect is the Prime Consultant then they should be considered the same term.

The **Consultant** is assumed to be a subconsultant on the project, handling the mechanical, electrical, or structural design, where the architect or other is the prime consultant.

Scope Creep is a problem that occurs when extra work is done that is not included in the original scope of work of the project and no additional fees are received. It is the addition, as development proceeds, of new features to a project that are above and beyond what the original contract called for.

The **Project Team** refers to all people working on the project from the owner, architect, consultants, subconsultants, etc.

APPENDIX E
Project Manager Interview

Project Manager Interview

Part A: Project Details

1. Name of Project: ______________________________
2. Project Date & Duration for Design: ______________________________
3. Project Date & Duration for Construction: ______________________________
4. Project Location: ______________________________
5. Proposal Stage Fee: $______________ or ______________%
6. Initial Project Fee: $______________ or ______________%
7. Final Project Fee (billed amount): $______________
8. Basis of fee (multiplier): __________

   If the multiplier is above 1.8 (or other standard), what is the reason for this?

   ____

   ____

   ____

   ____

9. Final (or actual) Cost: $______________
10. Was there a cost overrun? YES NO

    If YES, how much? $______________ or ______________%

    If YES, do you consider this cost overrun to be HIGH, MEDIUM, or LOW ?
11. Name of Architect or Prime Consultant: ______________________________
12. Name of Owner: ______________________________
13. Did you pursue any additional costs? YES NO

    If YES,

    Which ones were you compensated for and how much?

    1. ______________________________ $__________
    2. ______________________________ $__________
    3. ______________________________ $__________

4. ______________________________ $__________
5. ______________________________ $__________

Which ones were you not compensated for, how much, and why?

1. ______________________________ $__________
2. ______________________________ $__________
3. ______________________________ $__________
4. ______________________________ $__________
5. ______________________________ $__________

14. In general, what do you consider to be the main causes of "Scope Creep"?

1. ____
2. ____
3. ____
4. ____

Part B: Project Characteristics

For this specific project, please rate the following project characteristics on a scale of 1 to 10. **5** is considered neutral with **10** being excellent and **0** being poor:

1.0 Willingness of the architect/prime consultant to approach the owner for extra fees.

Poor 0 1 2 3 4 5 6 7 8 9 10 **Excellent**

2.0 Time taken by the owner/prime consultant/architect/engineer to make decisions.

Poor 0 1 2 3 4 5 6 7 8 9 10 **Excellent**

3.0 Knowledge base of the owner.

Poor 0 1 2 3 4 5 6 7 8 9 10 **Excellent**

4.0 Level of project scope definition between the consultant and owner/prime consultant at the proposal stage.

Poor 0 1 2 3 4 5 6 7 8 9 10 **Excellent**

5.0 Definition of scope duties passed on by the consultant's project manager to the design team.

Poor 0 1 2 3 4 5 6 7 8 9 10 **Excellent**

6.0 Experience of the consultant's project manager.

Poor 0 1 2 3 4 5 6 7 8 9 10 **Excellent**

7.0 Experience of prime consultant's project lead.

Poor 0 1 2 3 4 5 6 7 8 9 10 **Excellent**

8.0 Skill set of the consultant's design team.

Poor 0 1 2 3 4 5 6 7 8 9 10 **Excellent**

9.0 Skill set of architect/engineer's design teams.

Poor 0 1 2 3 4 5 6 7 8 9 10 **Excellent**

10.0 Experience of the project team with similar projects

Poor 0 1 2 3 4 5 6 7 8 9 10 **Excellent**

11.0 Project complexity.

Complex 0 1 2 3 4 5 6 7 8 9 10 **Simple**

12.0 Timeline for design and construction.

Too Short 0 1 2 3 4 5 6 7 8 9 10 **Too Long**

13.0 Project location (Remote is > 2 hours from consultant's office).

Remote 0 1 2 3 4 5 6 7 8 9 10 **Local**

Part C: Risk Events & Opportunities

For this specific project, please specify the degree to which these risk events occurred during the project on a scale of 1 to 10 (worst case meaning that very large problems resulted; best case meaning that a possible cost savings resulted; **5** meaning the event had a neutral effect on project cost):

I. Accuracy of site investigation N/A ☐

Worst case 0 1 2 3 4 5 6 7 8 9 10 **Best case**

II. Design errors or omissions N/A ☐

Worst case 0 1 2 3 4 5 6 7 8 9 10 **Best case**

III. Scope/design changes by the owner, consultants, or architect N/A ☐

Worst case 0 1 2 3 4 5 6 7 8 9 10 **Best case**

IV. Communication amongst the project team N/A ☐

Worst case 0 1 2 3 4 5 6 7 8 9 10 **Best case**

V. Over-engineering N/A ☐

Worst case 0 1 2 3 4 5 6 7 8 9 10 **Best case**

VI. Constructability issues N/A ☐

Worst case 0 1 2 3 4 5 6 7 8 9 10 **Best case**

VII. Inadequate design team resources N/A ☐

Worst case 0 1 2 3 4 5 6 7 8 9 10 **Best case**

VIII. General contractor and subcontractors. N/A ☐

Worst case 0 1 2 3 4 5 6 7 8 9 10 **Best case**

APPENDIX F
Results of the Expert Interview

Table 1. Standard Strengths between Project Characteristics and Risk/Opportunity Events – Worst Case Scenario

Risk Events / Project Characteristics	I. Poor site investigation	II. Design errors	III. Design/scope Changes	IV. Poor communication	V. Over-engineering	VI. Poor constructability	VII. Inadequate design resources	VIII. Poor general contractor
1.0 Willingness to approach owner	10	0	10	0	0	0	0	10
2.0 Time taken for decisions	5	3	10	8	7	10	8	7
3.0 Knowledge base of owner	5	0	10	3	3	2	3	9
4.0 Level of proj scope definition	6	10	10	9	2	1	6	0
5.0 Definition of designers duties	10	10	9	10	8	7	10	8
6.0 Experience of consultant's PM	10	10	10	10	10	10	10	10
7.0 Experience of architect lead	4	3	6	10	7	10	1	10
8.0 Skill set of consultant designers	10	10	8	10	6	10	10	10
9.0 Skill set of architect designers	2	8	2	7	0	2	8	10
10.0 Experience with similar proj	9	10	8	10	10	5	10	7
11.0 Project complexity	7	9	9	10	2	10	10	10
12.0 Timeline	10	8	8	10	0	9	10	10
13.0 Project location	5	0	0	2	2	10	0	10

Table 2. Standard Strengths between Project Characteristics and Risk/Opportunity Events – Best Case Scenario

Risk Events / Project Characteristics	I. Good site investigation	II. No design errors	III. No Design/scope changes	IV. Excellent communica-tion	V. No over-engineering	VI. Excellent constructa-bility	VII. Adequate design resources	VIII. Excellent general contractor
1.0 Willingness to approach owner	8	0	0	2	0	0	0	0
2.0 Time taken for decisions	8	2	2	2	2	2	2	2
3.0 Knowledge base of owner	2	0	1	1	0	0	0	0
4.0 Level of proj scope definition	4	4	4	2	4	0	4	0
5.0 Definition of designers duties	5	3	3	3	3	0	3	0
6.0 Experience of consultant's PM	5	5	5	5	5	5	5	2
7.0 Experience of architect lead	2	0	2	3	0	0	0	2
8.0 Skill set of consultant designers	3	3	3	1	3	3	3	0
9.0 Skill set of architect designers	0	0	0	0	0	0	0	0
10.0 Experience with similar proj	2	2	2	2	2	2	2	2
11.0 Project complexity	3	0	1	1	1	2	1	1
12.0 Timeline	5	4	4	3	0	3	4	2
13.0 Project location	1	0	0	3	0	3	0	2

Table 3. Cost Overruns/Underruns resulting from Project Characteristics and Risk Events – Worst Case Scenario

Risk Events / Project Characteristics	I. Poor site investigation	II. Design errors	III. Design/scope Changes	IV. Poor communication	V. Over-engineering	VI. Poor constructability	VII. Inadequate design resources	VIII. Poor general contractor
1.0 Unwilling to approach owner	5-10%	0	5-10%	0	0	0	0	0-5%
2.0 Time taken for decisions slow	5-10%	0-5%	5-10%	5-10%	0	0	0-5%	5-10%
3.0 Knowledge base of owner low	0-5%	0	5-10%	0-5%	0	0	0	5-10%
4.0 Level of proj scope def'n low	5-10%	5-10%	5-10%	5-10%	5-10%	5-10%	20^{+}%	5-10%
5.0 Poor def'n of designers duties	0-5%	5-10%	5-10%	5-10%	5-10%	5-10%	20^{+}%	0
6.0 Experience of consultant PM low	5-10%	5-10%	5-10%	5-10%	5-10%	5-10%	20^{+}%	5-10%
7.0 Experience of architect lead low	0-5%	0	5-10%	5-10%	0	0-5%	0	5-10%
8.0 Low skill of consultant designers	5-10%	5-10%	5-10%	0-5%	5-10%	5-10%	5-10%	0
9.0 Low skill of architect designers	0-5%	0	5-10%	5-10%	0	0-5%	5-10%	0
10.0 No exp. with similar projects	5-10%	20^{+}%	5-10%	5-10%	5-10%	5-10%	5-10%	5-10%
11.0 High project complexity	5-10%	5-10%	5-10%	5-10%	0-5%	5-10%	5-10%	5-10%
12.0 Short Timeline	0-5%	5-10%	5-10%	5-10%	0-5%	5-10%	5-10%	5-10%
13.0 Project location remote	5-10%	0	0-5%	5-10%	0	5-10%	0	5-10%

Table 4. Cost Overruns/Underruns resulting from Project Characteristics and Opportunity Events – Best Case Scenario

Risk Events / Project Characteristics	I. Good site investigation	II. No design errors	III. No Design/scope changes	IV. Excellent communica-tion	V. No over-engineering	VI. Excellent constructa-bility	VII. Adequate design resources	VIII. Excellent general contractor
1.0 Willing to approach owner	0	0	0	0	0	0	0	0
2.0 Time taken for decisions fast	0-~5%	0-~5%	0-~5%	0-~5%	0-~5%	0-~5%	0-~5%	0-~5%
3.0 Knowledge base of owner high	0-~5%	0-~5%	0-~5%	~5-~10%	0	0	0-~5%	0-~5%
4.0 Level of proj scope def'n high	~5-~10%	~5-~10%	~5-~10%	~5-~10%	0-~5%	0-~5%	~5-~10%	0-~5%
5.0 High def'n of designers duties	~5-~10%	0-~5%	0-~5%	~5-~10%	0-~5%	0-~5%	~5-~10%	0
6.0 Experience of consultant PM high	~5-~10%	~10-~20%	0-~5%	~5-~10%	~5-~10%	0-~5%	~10-~20%	~5-~10%
7.0 Experience of architect lead high	0-~5%	0-~5%	~5-~10%	~5-~10%	0	0-~5%	0-~5%	~5-~10%
8.0 High skill of consultant designers	~5-~10%	~5-~10%	0-~5%	~5-~10%	~5-~10%	0-~5%	~5-~10%	0
9.0 High skill of architect designers	0-~5%	0	0-~5%	0-~5%	0	0-~5%	~5-~10%	0
10.0 Exp. with similar proj high	0-~5%	~5-~10%	0-~5%	~5-~10%	~5-~10%	~5-~10%	~10-~20%	0-~5%
11.0 Project complexity simple	0-~5%	0-~5%	0-~5%	~5-~10%	~5-~10%	0-~5%	~5-~10%	0-~5%
12.0 Adequate Timeline	~5-~10%	~5-~10%	0-~5%	~5-~10%	~5-~10%	0-~5%	~5-~10%	~5-~10%
13.0 Project location local	0-~5%	0-~5%	0-~5%	~5-~10%	0	0-~5%	0	0-~5%

APPENDIX G

Data from the Project Manager Interviews

Table G.1 Model Testing Data

	Cost Overrun/Underrun		1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0
	($)	(%)	I	II	III	IV	V	VI	VII	VIII					
A	($64,693.22)	-38%	6	9	7	7	7	5	9	10	9	8	5	5	0
			10	[illegible]	5	8	4	4	7	3					
B	($6,401.00)	-4%	7	5	8	8	8	6	4	8	5	7	1	4	10
			8	3	4	2	5	8	6	7					
C	$1,220.86	3%	5	4	7	8	8	7	6	7	5	5	6	4	8
			6	3	2	2	5	3	4	4					
D	($76,986.00).	-22%	8	8	7	6	7	7	7	7	7	7	8	6	0
			6	8	7	7	8	4	8	7					
E	$5,000.00	2%	4	2	6	4	7	7	5	7	5	6	1	7	10
			8	6	4	6	8	8	7	4					
F	$58,000.00	63%	1	6	7	1	6	4	6	6	6	6	1	4	10
			0	4	6	6	8	4	8	3					
G	$8,920.00	6%	0	4	7	5	8	9	6	7	6	8	9	3	10
			7	4	3	4	3	3	5	7					
H	$2,952.00	54%	1	3	3	6	4	6	2	2	2	2	7	5	10
			6	7	3	3	0	6	3	5					
I	$4,460.00	75%	1	3	3	6	4	6	2	2	2	2	7	5	10
			6	7	3	3	0	6	3	5					
J	$26,480.00	78%	1	3	5	6	6	8	5	8	6	8	2	8	1
			8	7	2	2	5	5	7	2					
K	($28,400.00)	-15%	8	2	7	8	8	7	7	7	8	8	7	4	0
			7	8	10	7	5	5	5	6					
L	($14,500.00)	-9%	9	9	7	7	8	9	9	7	8	8	5	8	0
			6	9	8	9	7	7	8	2					
M	$15,000.00	14%	6	4	9	6	5	7	3	8	3	3	5	5	9
			8	2	7	0	3	7	7	2					
N	($16,745.00)	-36%	7	8	7	10	10	10	10	9	5	9	6	4	9
			7	5	5	7	5	4	5	5					
O	$11,484.00	17%	1	3	3	2	5	3	5	4	4	3	2	4	0
			3	4	4	6	5	5	4	2					
P	($2,022.00)	-25%	10	7	6	10	10	10	10	6	6	10	5	5	10
			10	10	10	10	5	5	8	10					
Q	$8,869.00	17%	10	4	5	7	7	10	10	8	7	8	8	1	10
			3	5	7	10	5	3	5	7					
R	$16,283.00	31%	6	1	6	1	4	10	7	7	7	7	7	3	1
			2	4	3	3	5	6	4	4					

Table G.2 Ratings of Project Characteristics

	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0
	6	9	7	7	7	5	9	10	9	8	5	5	0
	7	5	8	8	8	6	4	8	5	7	1	4	10
	5	4	7	8	8	7	6	7	5	5	6	4	8
	8	8	7	6	7	7	7	7	7	7	8	6	0
	4	2	6	4	7	7	5	7	5	6	1	7	10
	1	6	7	1	6	4	6	6	6	6	1	4	10
	0	4	7	5	8	9	6	7	6	8	9	3	10
	1	3	3	6	4	6	2	2	2	2	7	5	10
	1	3	3	6	4	6	2	2	2	2	7	5	10
	1	3	5	6	6	8	5	8	6	8	2	8	1
	8	2	7	8	8	7	7	7	8	8	7	4	0
	9	9	7	7	8	9	9	7	8	8	5	8	0
	6	4	9	6	5	7	3	8	3	3	5	5	9
	7	8	7	10	10	10	10	9	5	9	6	4	9
	1	3	3	2	5	3	5	4	4	3	2	4	0
	10	7	6	10	10	10	10	6	6	10	5	5	10
	10	4	5	7	7	10	10	8	7	8	8	1	10
	6	1	6	1	4	10	7	7	7	7	7	3	1
Total Rating	91	85	110	108	122	131	113	120	101	115	92	85	108
Average Rating	5.1	4.7	6.1	6.0	6.8	7.3	6.3	6.7	5.6	6.4	5.1	4.7	6.0

Table G.3 Ratings of Risk Events

	I	II	III	IV	V	VI	VII	VIII
	10	6	5	8	4	4	7	3
	8	3	4	2	5	8	6	7
	6	3	2	2	5	3	4	4
	6	8	7	7	8	4	8	7
	8	6	4	6	8	8	7	4
	0	4	6	6	8	4	8	3
	7	4	3	4	3	3	5	7
	6	7	3	3	0	6	3	5
	6	7	3	3	0	6	3	5
	8	7	2	2	5	5	7	2
	7	8	5	7	5	5	5	6
	6	9	8	9	7	7	8	2
	8	2	7	0	3	7	7	2
	7	5	5	7	5	4	5	5
	3	4	4	6	5	5	4	2
	10	10	10	10	5	5	8	10
	3	5	7	10	5	3	5	7
	2	4	3	3	5	6	4	4
Total Rating	111	102	88	95	86	93	104	85
Average Rating	6.2	5.7	4.9	5.3	4.8	5.2	5.8	4.7

Table G.4 Frequency of Project Characteristic Ratings

	0 to 3	4 to 6	7 to 10
1.0	6	5	7
2.0	7	6	5
3.0	3	5	10
4.0	3	7	8
5.0	0	7	11
6.0	1	5	12
7.0	3	7	8
8.0	2	3	13
9.0	3	9	6
10.0	4	3	11
11.0	5	6	7
12.0	3	12	3
13.0	7	0	11

Table G.5 Frequency of Risk Event Ratings

	0 to 3	4 to 6	7 to 10
I	4	5	9
II	3	8	7
III	6	7	5
IV	7	4	7
V	4	10	4
VI	3	11	4
VII	2	8	8
VIII	6	7	5

APPENDIX H
Visual Basic 6.0 Programming Code

```
'  WORST-CASE MODEL

' Define all the standard strengths between the
' project characteristics and the risk events

Dim SS1(12, 7) As Single
    SS1(0, 0) = 1
    SS1(0, 1) = 0
    SS1(0, 2) = 1
    SS1(0, 3) = 0
    SS1(0, 4) = 0
    SS1(0, 5) = 0
    SS1(0, 6) = 0
    SS1(0, 7) = 1

    SS1(1, 0) = 0.5
    SS1(1, 1) = 0.3
    SS1(1, 2) = 1
    SS1(1, 3) = 0.8
    SS1(1, 4) = 0.7
    SS1(1, 5) = 1
    SS1(1, 6) = 0.8
    SS1(1, 7) = 0.7

    SS1(2, 0) = 0.5
    SS1(2, 1) = 0
    SS1(2, 2) = 1
    SS1(2, 3) = 0.3
    SS1(2, 4) = 0.3
    SS1(2, 5) = 0.2
    SS1(2, 6) = 0.3
    SS1(2, 7) = 0.9

    SS1(3, 0) = 0.6
    SS1(3, 1) = 1
    SS1(3, 2) = 1
    SS1(3, 3) = 0.9
    SS1(3, 4) = 0.2
    SS1(3, 5) = 0.1
    SS1(3, 6) = 0.6
    SS1(3, 7) = 0

    SS1(4, 0) = 1
    SS1(4, 1) = 1
    SS1(4, 2) = 0.9
    SS1(4, 3) = 1
    SS1(4, 4) = 0.8
    SS1(4, 5) = 0.7
```

```
SS1(4, 6) = 1
SS1(4, 7) = 0.8

SS1(5, 0) = 1
SS1(5, 1) = 1
SS1(5, 2) = 1
SS1(5, 3) = 1
SS1(5, 4) = 1
SS1(5, 5) = 1
SS1(5, 6) = 1
SS1(5, 7) = 1

SS1(6, 0) = 0.4
SS1(6, 1) = 0.3
SS1(6, 2) = 0.6
SS1(6, 3) = 1
SS1(6, 4) = 0.7
SS1(6, 5) = 1
SS1(6, 6) = 0.1
SS1(6, 7) = 1

SS1(7, 0) = 1
SS1(7, 1) = 1
SS1(7, 2) = 0.8
SS1(7, 3) = 1
SS1(7, 4) = 0.6
SS1(7, 5) = 1
SS1(7, 6) = 1
SS1(7, 7) = 1

SS1(8, 0) = 0.2
SS1(8, 1) = 0.8
SS1(8, 2) = 0.2
SS1(8, 3) = 0.7
SS1(8, 4) = 0
SS1(8, 5) = 0.2
SS1(8, 6) = 0.8
SS1(8, 7) = 1

SS1(9, 0) = 0.9
SS1(9, 1) = 1
SS1(9, 2) = 0.8
SS1(9, 3) = 1
SS1(9, 4) = 1
SS1(9, 5) = 0.5
SS1(9, 6) = 1
SS1(9, 7) = 0.7

SS1(10, 0) = 0.7
SS1(10, 1) = 0.9
SS1(10, 2) = 0.9
SS1(10, 3) = 1
```

```
    SS1(10, 4) = 0.2
    SS1(10, 5) = 1
    SS1(10, 6) = 1
    SS1(10, 7) = 1

    SS1(11, 0) = 1
    SS1(11, 1) = 0.8
    SS1(11, 2) = 0.8
    SS1(11, 3) = 1
    SS1(11, 4) = 0
    SS1(11, 5) = 0.9
    SS1(11, 6) = 1
    SS1(11, 7) = 1

    SS1(12, 0) = 0.5
    SS1(12, 1) = 0
    SS1(12, 2) = 0
    SS1(12, 3) = 0.2
    SS1(12, 4) = 0.2
    SS1(12, 5) = 1
    SS1(12, 6) = 0
    SS1(12, 7) = 1


' Define the cost overrun/underrun percentage
' categories

Dim C(9) As Single
    C(0) = 0
    C(1) = 1
    C(2) = 2
    C(3) = 3
    C(4) = 4
    C(5) = 5
    C(6) = 6
    C(7) = 7
    C(8) = 8
    C(9) = 9


' Define the expected cost overrun for each pair
' of characteristic and risk event (worst case scenario)

Dim SS2(12, 7) As Single
    SS2(0, 0) = C(7)
    SS2(0, 1) = C(5)
    SS2(0, 2) = C(8)
    SS2(0, 3) = C(5)
    SS2(0, 4) = C(5)
    SS2(0, 5) = C(5)
    SS2(0, 6) = C(5)
    SS2(0, 7) = C(6)
```

```
SS2(1, 0) = C(7)
SS2(1, 1) = C(6)
SS2(1, 2) = C(7)
SS2(1, 3) = C(7)
SS2(1, 4) = C(5)
SS2(1, 5) = C(5)
SS2(1, 6) = C(6)
SS2(1, 7) = C(7)

SS2(2, 0) = C(6)
SS2(2, 1) = C(5)
SS2(2, 2) = C(7)
SS2(2, 3) = C(6)
SS2(2, 4) = C(5)
SS2(2, 5) = C(5)
SS2(2, 6) = C(5)
SS2(2, 7) = C(7)

SS2(3, 0) = C(7)
SS2(3, 1) = C(7)
SS2(3, 2) = C(8)
SS2(3, 3) = C(8)
SS2(3, 4) = C(8)
SS2(3, 5) = C(7)
SS2(3, 6) = C(9)
SS2(3, 7) = C(8)

SS2(4, 0) = C(6)
SS2(4, 1) = C(7)
SS2(4, 2) = C(7)
SS2(4, 3) = C(7)
SS2(4, 4) = C(7)
SS2(4, 5) = C(7)
SS2(4, 6) = C(9)
SS2(4, 7) = C(5)

SS2(5, 0) = C(7)
SS2(5, 1) = C(8)
SS2(5, 2) = C(8)
SS2(5, 3) = C(7)
SS2(5, 4) = C(8)
SS2(5, 5) = C(7)
SS2(5, 6) = C(9)
SS2(5, 7) = C(7)

SS2(6, 0) = C(6)
SS2(6, 1) = C(5)
SS2(6, 2) = C(7)
SS2(6, 3) = C(8)
SS2(6, 4) = C(5)
SS2(6, 5) = C(6)
```

```
SS2(6, 6) = C(5)
SS2(6, 7) = C(8)

SS2(7, 0) = C(7)
SS2(7, 1) = C(7)
SS2(7, 2) = C(7)
SS2(7, 3) = C(6)
SS2(7, 4) = C(8)
SS2(7, 5) = C(7)
SS2(7, 6) = C(8)
SS2(7, 7) = C(5)

SS2(8, 0) = C(6)
SS2(8, 1) = C(5)
SS2(8, 2) = C(7)
SS2(8, 3) = C(7)
SS2(8, 4) = C(5)
SS2(8, 5) = C(6)
SS2(8, 6) = C(7)
SS2(8, 7) = C(5)

SS2(9, 0) = C(8)
SS2(9, 1) = C(9)
SS2(9, 2) = C(8)
SS2(9, 3) = C(7)
SS2(9, 4) = C(8)
SS2(9, 5) = C(7)
SS2(9, 6) = C(8)
SS2(9, 7) = C(8)

SS2(10, 0) = C(7)
SS2(10, 1) = C(8)
SS2(10, 2) = C(7)
SS2(10, 3) = C(7)
SS2(10, 4) = C(6)
SS2(10, 5) = C(7)
SS2(10, 6) = C(8)
SS2(10, 7) = C(8)

SS2(11, 0) = C(6)
SS2(11, 1) = C(7)
SS2(11, 2) = C(7)
SS2(11, 3) = C(8)
SS2(11, 4) = C(6)
SS2(11, 5) = C(7)
SS2(11, 6) = C(8)
SS2(11, 7) = C(8)

SS2(12, 0) = C(7)
SS2(12, 1) = C(5)
SS2(12, 2) = C(6)
SS2(12, 3) = C(7)
```

```
    SS2(12, 4) = C(5)
    SS2(12, 5) = C(8)
    SS2(12, 6) = C(5)
    SS2(12, 7) = C(8)


' Calculations for the S(P,R) relation
Dim S(12, 7) As Single
Dim i, k As Integer
    i = k = 0
    For i = 0 To 12
    For k = 0 To 7
        S(i, k) = (1 - (frmData.txtwP(i)) / 10) * (1 -
                    (frmData.txtwR(k) / 10)) * SS1(i, k)
    Next k
    Next i


' Assign values for the F(R,C) relation
Dim F(103, 9) As Single
Dim a As Integer
    i = k = 0
    a = 0
    For i = 0 To 12
    For k = 0 To 7
        If SS2(i, k) = C(5) Then
            F(a, 5) = 1
            F(a, 6) = 0.8
            F(a, 7) = 0.6
            F(a, 8) = 0.4
            F(a, 9) = 0.2
        ElseIf SS2(i, k) = C(6) Then
            F(a, 5) = 0.8
            F(a, 6) = 1
            F(a, 7) = 0.8
            F(a, 8) = 0.6
            F(a, 9) = 0.4
        ElseIf SS2(i, k) = C(7) Then
            F(a, 5) = 0.6
            F(a, 6) = 0.8
            F(a, 7) = 1
            F(a, 8) = 0.8
            F(a, 9) = 0.6
        ElseIf SS2(i, k) = C(8) Then
            F(a, 5) = 0.4
            F(a, 6) = 0.6
            F(a, 7) = 0.8
            F(a, 8) = 1
            F(a, 9) = 0.8
        ElseIf SS2(i, k) = C(9) Then
            F(a, 5) = 0.2
            F(a, 6) = 0.4
            F(a, 7) = 0.6
            F(a, 8) = 0.8
            F(a, 9) = 1
        End If
        a = a + 1
    Next k
    Next i

' Calculate values for Q(P,C) relation using
' cum-min composition operation
    Dim Q(12, 9) As Single
    Dim n As Integer
    Dim Qmin As Single
        i = n = k = 0
        a = 0
        For n = 0 To 9
        For i = 0 To 12
        For k = 0 To 7
            If S(i, k) < F(a, n) Then
                Qmin = S(i, k)
            Else
                Qmin = F(a, n)
            End If
            Q(i, n) = Qmin + Q(i, n)
            Qmin = 0
        a = a + 1
        Next k
        Next i
        a = 0
        Next n

' Calculate the sum of the inputted project
' characteristic wieghts
    Dim wP As Single
        i = wP = 0
        For i = 0 To 12
            wP = (1 - (frmData.txtwP(i)) / 10) + wP
        Next i

' Add up the values in the columns of the Q(P,C)
' matrix and divide by the sum of the project
' characteristic weights
    Dim Sum(9) As Single
    Dim Qsum As Single
        n = i = Qsum = 0
        For n = 0 To 9
        For i = 0 To 12
            Qsum = Q(i, n) + Qsum
        Next i
            Sum(n) = Qsum / wP
            Qsum = 0
        Next n
```

```
' BEST-CASE MODEL

' Define all the standard strengths between the
' project characteristics and the risk events

Dim gSS1(12, 7) As Single
    gSS1(0, 0) = 0.8
    gSS1(0, 1) = 0
    gSS1(0, 2) = 0
    gSS1(0, 3) = 0.2
    gSS1(0, 4) = 0
    gSS1(0, 5) = 0
    gSS1(0, 6) = 0
    gSS1(0, 7) = 0

    gSS1(1, 0) = 0.8
    gSS1(1, 1) = 0.2
    gSS1(1, 2) = 0.2
    gSS1(1, 3) = 0.2
    gSS1(1, 4) = 0.2
    gSS1(1, 5) = 0.2
    gSS1(1, 6) = 0.2
    gSS1(1, 7) = 0.2

    gSS1(2, 0) = 0.2
    gSS1(2, 1) = 0
    gSS1(2, 2) = 0.1
    gSS1(2, 3) = 0.1
    gSS1(2, 4) = 0
    gSS1(2, 5) = 0
    gSS1(2, 6) = 0
    gSS1(2, 7) = 0

    gSS1(3, 0) = 0.4
    gSS1(3, 1) = 0.4
    gSS1(3, 2) = 0.4
    gSS1(3, 3) = 0.2
    gSS1(3, 4) = 0.4
    gSS1(3, 5) = 0
    gSS1(3, 6) = 0.4
    gSS1(3, 7) = 0

    gSS1(4, 0) = 0.5
    gSS1(4, 1) = 0.3
    gSS1(4, 2) = 0.3
    gSS1(4, 3) = 0.3
    gSS1(4, 4) = 0.3
    gSS1(4, 5) = 0
    gSS1(4, 6) = 0.3
    gSS1(4, 7) = 0
```

```
gSS1(5, 0) = 0.5
gSS1(5, 1) = 0.5
gSS1(5, 2) = 0.5
gSS1(5, 3) = 0.5
gSS1(5, 4) = 0.5
gSS1(5, 5) = 0.5
gSS1(5, 6) = 0.5
gSS1(5, 7) = 0.2

gSS1(6, 0) = 0.2
gSS1(6, 1) = 0
gSS1(6, 2) = 0.2
gSS1(6, 3) = 0.3
gSS1(6, 4) = 0
gSS1(6, 5) = 0
gSS1(6, 6) = 0
gSS1(6, 7) = 0.2

gSS1(7, 0) = 0.3
gSS1(7, 1) = 0.3
gSS1(7, 2) = 0.3
gSS1(7, 3) = 0.1
gSS1(7, 4) = 0.3
gSS1(7, 5) = 0.3
gSS1(7, 6) = 0.3
gSS1(7, 7) = 0

gSS1(8, 0) = 0
gSS1(8, 1) = 0
gSS1(8, 2) = 0
gSS1(8, 3) = 0
gSS1(8, 4) = 0
gSS1(8, 5) = 0
gSS1(8, 6) = 0
gSS1(8, 7) = 0

gSS1(9, 0) = 0.2
gSS1(9, 1) = 0.2
gSS1(9, 2) = 0.2
gSS1(9, 3) = 0.2
gSS1(9, 4) = 0.2
gSS1(9, 5) = 0.2
gSS1(9, 6) = 0.2
gSS1(9, 7) = 0.2

gSS1(10, 0) = 0.3
gSS1(10, 1) = 0
gSS1(10, 2) = 0.1
gSS1(10, 3) = 0.1
gSS1(10, 4) = 0.1
gSS1(10, 5) = 0.2
```

```
    gSS1(10, 6) = 0.1
    gSS1(10, 7) = 0.1

    gSS1(11, 0) = 0.5
    gSS1(11, 1) = 0.4
    gSS1(11, 2) = 0.4
    gSS1(11, 3) = 0.3
    gSS1(11, 4) = 0
    gSS1(11, 5) = 0.3
    gSS1(11, 6) = 0.4
    gSS1(11, 7) = 0.2

    gSS1(12, 0) = 0.1
    gSS1(12, 1) = 0
    gSS1(12, 2) = 0
    gSS1(12, 3) = 0.3
    gSS1(12, 4) = 0
    gSS1(12, 5) = 0.3
    gSS1(12, 6) = 0
    gSS1(12, 7) = 0.2


' Define the expected cost overrun/underrun for
' each pair of characteristic and risk event

Dim gSS2(12, 7) As Single
    gSS2(0, 0) = C(4)
    gSS2(0, 1) = C(4)
    gSS2(0, 2) = C(4)
    gSS2(0, 3) = C(4)
    gSS2(0, 4) = C(4)
    gSS2(0, 5) = C(4)
    gSS2(0, 6) = C(4)
    gSS2(0, 7) = C(4)

    gSS2(1, 0) = C(3)
    gSS2(1, 1) = C(3)
    gSS2(1, 2) = C(3)
    gSS2(1, 3) = C(3)
    gSS2(1, 4) = C(3)
    gSS2(1, 5) = C(3)
    gSS2(1, 6) = C(3)
    gSS2(1, 7) = C(3)

    gSS2(2, 0) = C(3)
    gSS2(2, 1) = C(3)
    gSS2(2, 2) = C(3)
    gSS2(2, 3) = C(2)
    gSS2(2, 4) = C(4)
    gSS2(2, 5) = C(4)
    gSS2(2, 6) = C(3)
    gSS2(2, 7) = C(3)
```

```
gSS2(3, 0) = C(2)
gSS2(3, 1) = C(2)
gSS2(3, 2) = C(2)
gSS2(3, 3) = C(2)
gSS2(3, 4) = C(3)
gSS2(3, 5) = C(3)
gSS2(3, 6) = C(2)
gSS2(3, 7) = C(3)

gSS2(4, 0) = C(2)
gSS2(4, 1) = C(3)
gSS2(4, 2) = C(3)
gSS2(4, 3) = C(2)
gSS2(4, 4) = C(3)
gSS2(4, 5) = C(3)
gSS2(4, 6) = C(2)
gSS2(4, 7) = C(4)

gSS2(5, 0) = C(2)
gSS2(5, 1) = C(1)
gSS2(5, 2) = C(3)
gSS2(5, 3) = C(2)
gSS2(5, 4) = C(2)
gSS2(5, 5) = C(3)
gSS2(5, 6) = C(1)
gSS2(5, 7) = C(2)

gSS2(6, 0) = C(3)
gSS2(6, 1) = C(3)
gSS2(6, 2) = C(2)
gSS2(6, 3) = C(2)
gSS2(6, 4) = C(4)
gSS2(6, 5) = C(3)
gSS2(6, 6) = C(3)
gSS2(6, 7) = C(2)

gSS2(7, 0) = C(2)
gSS2(7, 1) = C(2)
gSS2(7, 2) = C(3)
gSS2(7, 3) = C(2)
gSS2(7, 4) = C(2)
gSS2(7, 5) = C(3)
gSS2(7, 6) = C(2)
gSS2(7, 7) = C(4)

gSS2(8, 0) = C(3)
gSS2(8, 1) = C(4)
gSS2(8, 2) = C(3)
gSS2(8, 3) = C(3)
gSS2(8, 4) = C(4)
gSS2(8, 5) = C(3)
```

```
    gSS2(8, 6) = C(2)
    gSS2(8, 7) = C(4)

    gSS2(9, 0) = C(3)
    gSS2(9, 1) = C(2)
    gSS2(9, 2) = C(3)
    gSS2(9, 3) = C(2)
    gSS2(9, 4) = C(2)
    gSS2(9, 5) = C(2)
    gSS2(9, 6) = C(1)
    gSS2(9, 7) = C(3)

    gSS2(10, 0) = C(3)
    gSS2(10, 1) = C(3)
    gSS2(10, 2) = C(3)
    gSS2(10, 3) = C(2)
    gSS2(10, 4) = C(2)
    gSS2(10, 5) = C(3)
    gSS2(10, 6) = C(2)
    gSS2(10, 7) = C(3)

    gSS2(11, 0) = C(2)
    gSS2(11, 1) = C(2)
    gSS2(11, 2) = C(3)
    gSS2(11, 3) = C(2)
    gSS2(11, 4) = C(2)
    gSS2(11, 5) = C(3)
    gSS2(11, 6) = C(2)
    gSS2(11, 7) = C(2)

    gSS2(12, 0) = C(3)
    gSS2(12, 1) = C(3)
    gSS2(12, 2) = C(3)
    gSS2(12, 3) = C(2)
    gSS2(12, 4) = C(4)
    gSS2(12, 5) = C(3)
    gSS2(12, 6) = C(4)
    gSS2(12, 7) = C(5)

' Calculations for the best-case S(P,R) relation
Dim gS(12, 7) As Single
    i = k = 0
    For i = 0 To 12
    For k = 0 To 7
        gS(i, k) = (frmData.txtwP(i)) / 10 * (frmData.txtwR(k)) /
                    10 * gSS1(i, k)
    Next k
    Next i
```

```
' Assign values for the best-case F(R,C) relation
Dim gF(103, 9) As Single
    i = k = 0
    a = 0
    For i = 0 To 12
    For k = 0 To 7
        If gSS2(i, k) = C(0) Then
            gF(a, 0) = 1#
            gF(a, 1) = 0.8
            gF(a, 2) = 0.6
            gF(a, 3) = 0.4
            gF(a, 4) = 0.2
        ElseIf gSS2(i, k) = C(1) Then
            gF(a, 0) = 0.8
            gF(a, 1) = 1
            gF(a, 2) = 0.8
            gF(a, 3) = 0.6
            gF(a, 4) = 0.4
        ElseIf gSS2(i, k) = C(2) Then
            gF(a, 0) = 0.6
            gF(a, 1) = 0.8
            gF(a, 2) = 1
            gF(a, 3) = 0.8
            gF(a, 4) = 0.6
        ElseIf gSS2(i, k) = C(3) Then
            gF(a, 0) = 0.4
            gF(a, 1) = 0.6
            gF(a, 2) = 0.8
            gF(a, 3) = 1
            gF(a, 4) = 0.8
        ElseIf gSS2(i, k) = C(4) Then
            gF(a, 0) = 0.2
            gF(a, 1) = 0.4
            gF(a, 2) = 0.6
            gF(a, 3) = 0.8
            gF(a, 4) = 1
        End If
        a = a + 1
    Next k
    Next i


' Calculate values for Q(P,C) relation using
' cum-min composition operation
    Dim gQ(12, 9) As Single
    Dim gQmin As Single
        i = n = k = 0
        a = 0
        For n = 0 To 9
        For i = 0 To 12
        For k = 0 To 7
            If gS(i, k) < gF(a, n) Then
```

```
                gQmin = gS(i, k)
            Else
                gQmin = gF(a, n)
            End If
            gQ(i, n) = gQmin + gQ(i, n)
            gQmin = 0
        a = a + 1
        Next k
        Next i
        a = 0
        Next n

' Calculate the sum of the inputted project
' characteristic wieghts
    Dim gwP As Single
        i = wP = 0
        For i = 0 To 12
            gwP = (frmData.txtwP(i)) / 10 + gwP
        Next i

' Add up the values in the columns of the Q(P,C)
' matrix and divide by the sum of the project
' characteristic weights
    Dim gSum(9) As Single
    Dim gQsum As Single
        n = i = gQsum = 0
        For n = 0 To 9
        For i = 0 To 12
            gQsum = gQ(i, n) + gQsum
        Next i
            gSum(n) = gQsum / gwP
            gQsum = 0
        Next n


' COMBINE THE TWO MODELS
' Add the summed values in the Q(P,C) relation
    Dim ComboSum(9) As Single
    n = 0
        For n = 0 To 9
            ComboSum(n) = Sum(n) + gSum(n)
        Next n


' Normalize the elements of the ComboSum matrix
    Dim ComboNorm(9) As Single
        n = Qnorm = 0
        For n = 0 To 9
            If ComboSum(n) > Qnorm Then
                Qnorm = ComboSum(n)
            End If
        Next n
        n = 0
        For n = 0 To 9
            ComboNorm(n) = ComboSum(n) / Qnorm
        Next n


' Apply the Centre of Area method to defuzzify
    Dim Addfuzz, defuzz, SumNorm As Single
        n = SumCombine = 0
        For n = 0 To 9
            SumNorm = ComboNorm(n) + SumNorm
        Next n

        Addfuzz = defuzz = 0
        C(0) = -35
        C(1) = -15
        C(2) = -7.5
        C(3) = -2.5
        C(4) = 0
        C(5) = 0
        C(6) = 2.5
        C(7) = 7.5
        C(8) = 15
        C(9) = 60

        For n = 0 To 9
            Addfuzz = (C(n)) * ComboNorm(n)
            defuzz = Addfuzz + defuzz
            Addfuzz = 0
        Next n
        defuzz = defuzz / SumNorm


' Get the calculated number to appear in the text box
        defuzz = Format(defuzz, "##")
        txtResult.Text = defuzz & " %"
```

APPENDIX I

Model Testing Results

Table I.1 Testing Results for Original Model

ACTUALS																		
Project	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Actual (%)	-38	-4	3	-22	2	63	6	54	75	78	-15	-9	14	-36	17	-25	17	31
Linguistic Range	0	3	5	0	5	8	6	8	8	8	1	2	7	0	7	0	7	8
PREDICTED																		
	Composition Operation: Cum-Min						**Defuzzification:** COA											
Predicted (%)	8	10	13	6	7	12	11	11	11	9	8	5	11	9	12	-2	9	13
Difference (%)	46	14	10	28	5	-51	5	-43	-64	-69	23	14	-3	45	-5	23	-8	-19
Ave Diff (%)	26																	
Linguistic Range	6	6	7	6	6	7	7	7	7	6	6	5	7	6	7	3	6	7
Range Difference	6	3	2	6	1	-1	1	-1	-1	-2	5	3	0	6	0	3	-1	-1
	Composition Operation: Max-Min						**Defuzzification:** COA											
Predicted	7	9	11	7	7	11	10	10	10	10	7	9	10	7	12	3	8	12
Difference	45	13	8	29	5	-52	4	-44	-65	-69	22	18	-4	43	-5	28	-9	-19
Ave Diff (%)	27																	
Linguistic Range	6	6	7	6	6	7	6	7	7	7	6	6	7	6	7	5	6	7
Range Difference	6	3	2	6	1	-1	0	-1	-1	-1	5	4	0	6	0	5	-1	-1
	Composition Operation: Cum-Min						**Defuzzification:** MOM											
Predicted	7.5	2.5	2.5	2.5	2.5	7.5	7.5	7.5	7.5	7.5	2.5	7.5	7.5	0	7.5	-2.5	2.5	7.5
Difference	45.5	6.5	-0.5	24.5	0.5	-55.5	1.5	-46.5	-67.5	-70.5	17.5	16.5	-6.5	36	-9.5	22.5	-14.5	-23.5
Ave Diff (%)	26																	
Linguistic Range	6	5	5	5	5	6	6	6	6	6	5	6	6	4	6	3	5	6
Range Difference	6	2	0	5	0	-2	0	-2	-2	-2	4	4	-1	4	-1	3	-2	-2

Table I.1 Testing Results for Original Model

ACTUALS																		
Project	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Actual (%)	-38	-4	3	-22	2	63	6	54	75	78	-15	-9	14	-36	17	-25	17	31
Linguistic Range	0	3	5	0	5	8	6	8	8	8	1	2	7	0	7	0	7	8
PREDICTED																		
	Composition Operation: Max-Min **Defuzzification:** MOM																	
Predicted	7.5	2.5	2.5	2.5	2.5	7.5	7.5	7.5	7.5	7.5	2.5	7.5	7.5	0	7.5	-2.5	0	7.5
Difference	45.5	6.5	-0.5	24.5	0.5	-55.5	1.5	-46.5	-67.5	-70.5	17.5	16.5	-6.5	36	-9.5	22.5	[illegible]	-23.5
Ave Diff (%)	26																	
Linguistic Range	6	5	5	5	5	6	6	6	6	6	5	6	6	4	6	3	4	6
Range Difference	6	2	0	5	0	-2	0	-2	-2	-2	4	4	-1	4	-1	3	-3	-2
	Composition Operation: Cum-Min **Defuzzification:** LOM																	
Predicted	10	5	5	5	5	10	10	10	10	10	5	10	10	0	10	0	5	10
Difference	48	9	2	27	3	-53	4	-44	-65	-68	20	19	-4	36	-7	25	-12	-21
Ave Diff (%)	26																	
Linguistic Range	6	5	5	5	5	7	6	7	7	7	5	6	7	3	7	3	6	7
Range Difference	6	2	0	5	0	-1	0	-1	-1	-1	4	4	0	3	0	3	-1	-1
	Composition Operation: Max-Min **Defuzzification:** LOM																	
Predicted	10	5	5	5	5	10	10	10	10	10	5	10	10	0	10	0	0	10
Difference	48	9	2	27	3	-53	4	-44	-65	-68	20	19	-4	36	-7	25	-17	-21
Ave Diff (%)	26																	
Linguistic Range	6	5	5	5	5	7	6	7	7	7	5	6	7	3	7	3	5	7
Range Difference	6	2	0	5	0	-1	0	-1	-1	-1	4	4	0	3	0	3	-2	-1

Table I.1 Testing Results for Original Model

ACTUALS																		
Project	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Actual (%)	-38	-4	3	-22	2	63	6	54	75	78	-15	-9	14	-36	17	-25	17	31
Linguistic Range	0	3	5	0	5	8	6	8	8	8	1	2	7	0	7	0	7	8
PREDICTED																		
	Composition Operation: Cum-Min						**Defuzzification:** SOM											
Predicted	5	0	0	0	0	5	5	5	5	5	0	5	5	0	5	-5	0	5
Difference	43	4	-3	22	-2	-58	-1	-49	-70	-73	15	14	-9	36	-12	20	-17	-26
Ave Diff (%)	26																	
Linguistic Range	5	3	5	3	5	6	6	6	6	6	3	5	6	3	6	2	5	6
Range Difference	5	0	0	3	0	-2	0	-2	-2	-2	2	3	-1	3	-1	2	-2	-2
	Composition Operation: Max-Min						**Defuzzification:** SOM											
Predicted	5	0	0	0	0	5	5	5	5	5	0	5	5	0	5	-5	0	5
Difference	43	4	-3	22	-2	-58	-1	-49	-70	-73	15	14	-9	36	-12	20	-17	-26
Ave Diff (%)	26																	
Linguistic Range	5	3	5	3	5	6	6	6	6	6	3	5	6	3	6	2	5	6
Range Difference	5	0	0	3	0	-2	0	-2	-2	-2	2	3	-1	3	-1	2	-2	-2

Linguistic Ranges:

0	Very High Underrun	-50% to -20%
1	High Underrun	-20% to -10%
2	Medium Underrun	-10% to -5%
3	Low Underrun	-5% to 0%
4	Zero	0%
5	Low Overrun	0% to 5%
6	Medium Overrun	5% to 10%
7	High Overrun	10% to 20%
8	Very High Overrun	20% to 100%

Table I.2 Testing Results for Calibrated Model

ACTUALS																		
Project	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	S1	S2	S3	S4	S5	S6	S7	S8
Actual (%)	-38	-4	-22	2	63	6	-15	-9	14	17	3	54	75	78	-36	-25	17	31
Linguistic Range	0	3	0	5	8	6	1	2	7	7	5	7	7	7	2	2	5	6
PREDICTED																		
	Composition Operation: Cum-Min							**Defuzzification:** COA										
Predicted (%)	3	6	1	3	8	7	1	0	7	8	20	15	15	8	6	-23	8	19
Difference (%)	41	10	23	1	-55	1	16	9	-7	-9	17	-39	-60	-70	42	2	-9	-12
Ave Diff (%)	10	(for large projects)									14	(for small projects)						
Linguistic Range	5	6	5	5	6	6	5	4	6	6	5	5	5	5	5	2	5	5
Range Difference	5	3	5	0	-2	0	4	2	-1	-1	0	-2	-2	-2	3	0	0	-1
	Composition Operation: Max-Min							**Defuzzification:** COA										
Predicted (%)	4	5	3	3	7	6	2	5	7	8	14	10	10	8	3	-9	5	18
Difference (%)	42	9	25	1	-56	0	17	14	-7	-9	11	-44	-65	-70	39	16	-12	-13
Ave Diff (%)	10	(for large projects)									15	(for small projects)						
Linguistic Range	5	5	5	5	6	6	5	5	6	6	5	5	5	5	5	3	5	5
Range Difference	5	2	5	0	-2	0	4	3	-1	-1	0	-2	-2	-2	3	1	0	-1
	Composition Operation: Cum-Min							**Defuzzification:** MOM										
Predicted (%)	7.5	2.5	-7.5	2.5	7.5	7.5	-7.5	-7.5	7.5	7.5	10	35	35	35	0	-35	10	35
Difference (%)	45.5	6.5	14.5	0.5	-55.5	1.5	7.5	1.5	-6.5	-9.5	7	-19	-40	-43	36	-10	-7	4
Ave Diff (%)	8	(for large projects)									9	(for small projects)						
Linguistic Range	6	5	2	5	6	6	2	2	6	6	5	6	6	6	4	2	5	6
Range Difference	6	2	2	0	-2	0	1	0	-1	-1	0	-1	-1	-1	2	0	0	0

Table I.2 Testing Results for Calibrated Model

ACTUALS																		
Project	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	S1	S2	S3	S4	S5	S6	S7	S8
Actual (%)	-38	-4	-22	2	63	6	-15	-9	14	17	3	54	75	78	-36	-25	17	31
Linguistic Range	0	3	0	5	8	6	1	2	7	7	5	7	7	7	2	2	5	6
PREDICTED																		
	Composition Operation: Max-Min							**Defuzzification:** MOM										
Predicted (%)	7.5	2.5	2.5	2.5	7.5	7.5	-7.5	7.5	7.5	7.5	10	35	35	35	0	-35	0	35
Difference (%)	45.5	6.5	24.5	0.5	-55.5	1.5	7.5	16.5	-6.5	-9.5	7	-19	-40	-43	36	-10	-17	4
Ave Diff (%)	10	(for large projects)									10	(for small projects)						
Linguistic Range	6	5	5	5	6	6	2	6	6	6	5	6	6	6	4	2	4	6
Range Difference	6	2	5	0	-2	0	1	4	-1	-1	0	-1	-1	-1	2	0	-1	0
	Composition Operation: Cum-Min							**Defuzzification:** LOM										
Predicted (%)	10	5	-5	5	10	10	-5	-5	10	10	20	50	50	50	0	-20	20	50
Difference (%)	48	9	17	3	-53	4	10	4	-4	-7	17	-4	-25	-28	36	5	3	50
Ave Diff (%)	9	(for large projects)									9	(for small projects)						
Linguistic Range	6	5	2	5	7	6	2	2	7	7	5	7	7	7	3	2	5	6
Range Difference	6	2	2	0	-1	0	1	0	0	0	0	0	0	0	1	0	0	0
	Composition Operation: Max-Min							**Defuzzification:** LOM										
Predicted (%)	10	5	5	5	10	10	-5	10	10	10	20	50	50	50	0	-20	0	50
Difference (%)	48	9	27	3	-53	4	10	19	-4	-7	17	-4	-25	-28	36	5	-17	19
Ave Diff (%)	10	(for large projects)									8	(for small projects)						
Linguistic Range	6	5	5	5	7	6	2	6	7	7	5	7	7	7	3	2	5	6
Range Difference	6	2	5	0	-1	0	1	4	0	0	0	0	0	0	1	0	0	0

Table I.2 Testing Results for Calibrated Model

ACTUALS																		
Project	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	S1	S2	S3	S4	S5	S6	S7	S8
Actual (%)	-38	-4	-22	2	63	6	-15	-9	14	17	3	54	75	78	-36	-25	17	31
Linguistic Range	0	3	0	5	8	6	1	2	7	7	5	7	7	7	2	2	5	6
PREDICTED																		
	Composition Operation: Cum-Min							**Defuzzification:** SOM										
Predicted (%)	5	0	-10	0	5	5	-10	-10	5	5	0	20	20	20	0	-50	0	20
Difference (%)	43	4	12	-2	-58	-1	5	-1	-9	-12	-3	-34	-55	-58	36	-25	-17	-11
Ave Diff (%)	8	(for large projects)									13	(for small projects)						
Linguistic Range	5	3	1	5	6	6	1	2	6	6	5	6	6	6	3	2	5	6
Range Difference	5	0	1	0	-2	0	0	0	-1	-1	0	-1	-1	-1	1	0	0	0
	Composition Operation: Max-Min							**Defuzzification:** SOM										
Predicted (%)	5	0	0	0	5	5	-10	5	5	5	0	20	20	20	0	-50	0	20
Difference (%)	43	4	22	-2	-58	-1	5	14	-9	-12	-3	-34	-55	-58	36	-25	-17	-11
Ave Diff (%)	9	(for large projects)									13	(for small projects)						
Linguistic Range	5	3	3	5	6	6	1	5	6	6	5	6	6	6	3	2	5	6
Range Difference	5	0	3	0	-2	0	0	3	-1	-1	0	-1	-1	-1	1	0	0	0

Linguistic Ranges:

Large Projects		
0	Very High Underrun	-50% to -20%
1	High Underrun	-20% to -10%
2	Medium Underrun	-10% to -5%
3	Low Underrun	-5% to 0%
4	Zero	0%
5	Low Overrun	0% to 5%
6	Medium Overrun	5% to 10%
7	High Overrun	10% to 20%
8	Very High Overrun	20% to 100%

Small Projects		
0	Very High Underrun	-100% to -80%
1	High Underrun	-80% to -50%
2	Medium Underrun	-50% to -20%
3	Low Underrun	-20% to 0%
4	Zero	0%
5	Low Overrun	0% to 20%
6	Medium Overrun	20% to 50%
7	High Overrun	50% to 80%
8	Very High Overrun	80% to 100%